Zooming-in on Instantons at HERA

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in collaboration with

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Plan

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3. **Rate and Final-State Signatures**
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http://www.desy.de/~t00fri/talks/talks.html

– Heidelberg, Jan 2001 –

1. Introduction

♣ Rich vacuum structure of non-abelian gauge theories like QCD $\Leftarrow$ 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 $\Leftrightarrow$ minimize classical action for $|Q| = 1$:
[Belavin *et al.* '75]

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

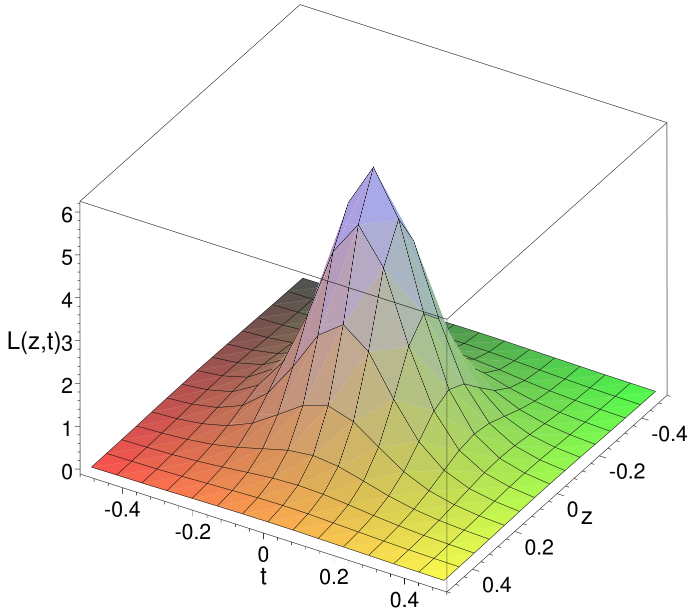
$$y = x - x_0 \quad \text{and} \quad \overline{y} = y_\nu \overline{\sigma}_\nu .$$

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

($\boldsymbol{I}$-position $x_0 = 0$:

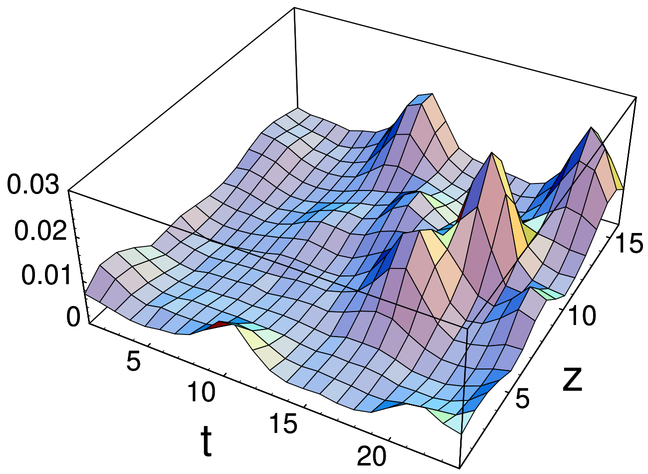
$$\mathcal{L}\left(A_\mu^{(I)}(x)\right) = \frac{12}{\pi\alpha} \cdot \frac{\rho^4}{(x^2+\rho^2)^4}$$

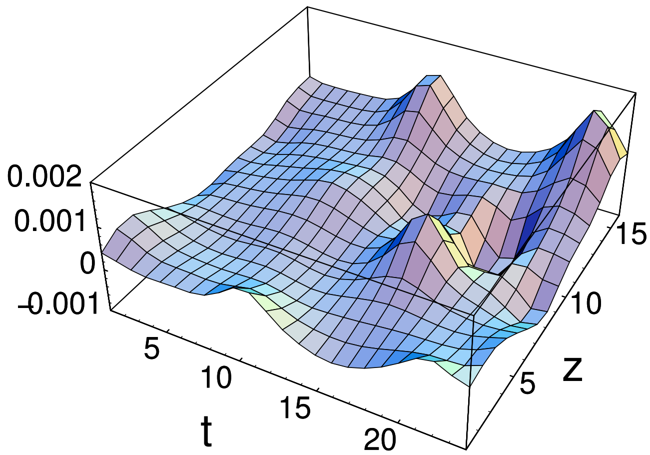
$$\Rightarrow \quad \boxed{S\left[A_\mu^{(I)}\right] = \frac{2\pi}{\alpha}}$$



- Realistic, non-perturbative lattice simulation, [Chu *et al.*'94], 3 $\boldsymbol{I}$'s und 2 $\overline{\boldsymbol{I}}$'s visible!

Lagrange Density **Topological Charge Density**





◇ Non-perturbative, topologically non-trivial fluctuations of gluon fields, localized ("instantaneous") in time und space

◇ In Minkowski space: Tunnelling transitions between adjacent, topologically inequivalent vacua, amplitude: $\sim \exp\left(-\frac{2\pi}{\alpha}\right)$.

- Lattice simulations (c.f. below)$\Rightarrow$ Typical $\boldsymbol{I}$-size $\rho \approx 0.5$ fm

  $\Leftrightarrow$ Theory: $\boldsymbol{I}$'s, important in transition region between partonic and hadronic description of strong interactions:

  - "U$_A(1)$ problem" $(m_{\eta'} \gg m_\eta)$; Veneziano-Witten relation; ['t Hooft '76, Veneziano '79, Witten '79, 't Hooft '00]
  - Breaking of chiral symmetry [Diakonov '96 (Review)]
  - Hadron and glueball spectrum [Schaefer, Shuryak '96 (review)]

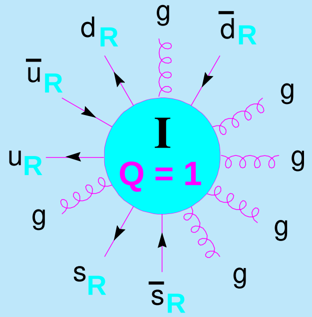
- Instantons, a basic non-perturbative aspect of QCD

- But direct experimental verification of instantons **lacking** up to now!

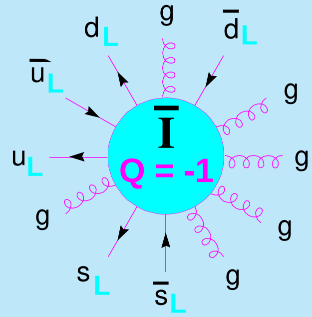
- **However. . .** [Ringwald & F. Sch. '94 - '00]

  Exploit characteristic manifestation of instantons at short distances for experimental search!

['t Hooft '76]: QCD -instantons induce hard processes with **violation of "chirality"** $\boxed{\chi = \#(q+\bar{q})_{\mathrm{R}} - \#(q+\bar{q})_{\mathrm{L}}}$



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



- ◇ forbidden in usual perturbation theory ($\mathcal{Q} = \mathbf{0}$!)
- ◇ Selection rule in agreement with the general Adler-Bell-Jackiw chiral ANOMALY relation for full QCD

♣ $\boxed{\text{Deep-inelastic scattering (DIS) at HERA}}$, a unique opportunity for discovery of these hard instanton-induced processes, due to

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

- ◇ a measurable rate,
  calculable in framework of "instanton-perturbation theory"
  [Ringwald & F. Sch., Phys. Lett **B459** (1999) 249; **B438** (1998) 217;
  Moch, Ringwald & F. Sch., Nucl. Phys. **B507** (1997) 134]

♣ Key-property: hard deep-inelastic scale $\mathcal{Q}$ suppresses instantons of large size, $\rho \gtrsim \mathcal{Q}^{-1}$, for which theoretical control is lacking!

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

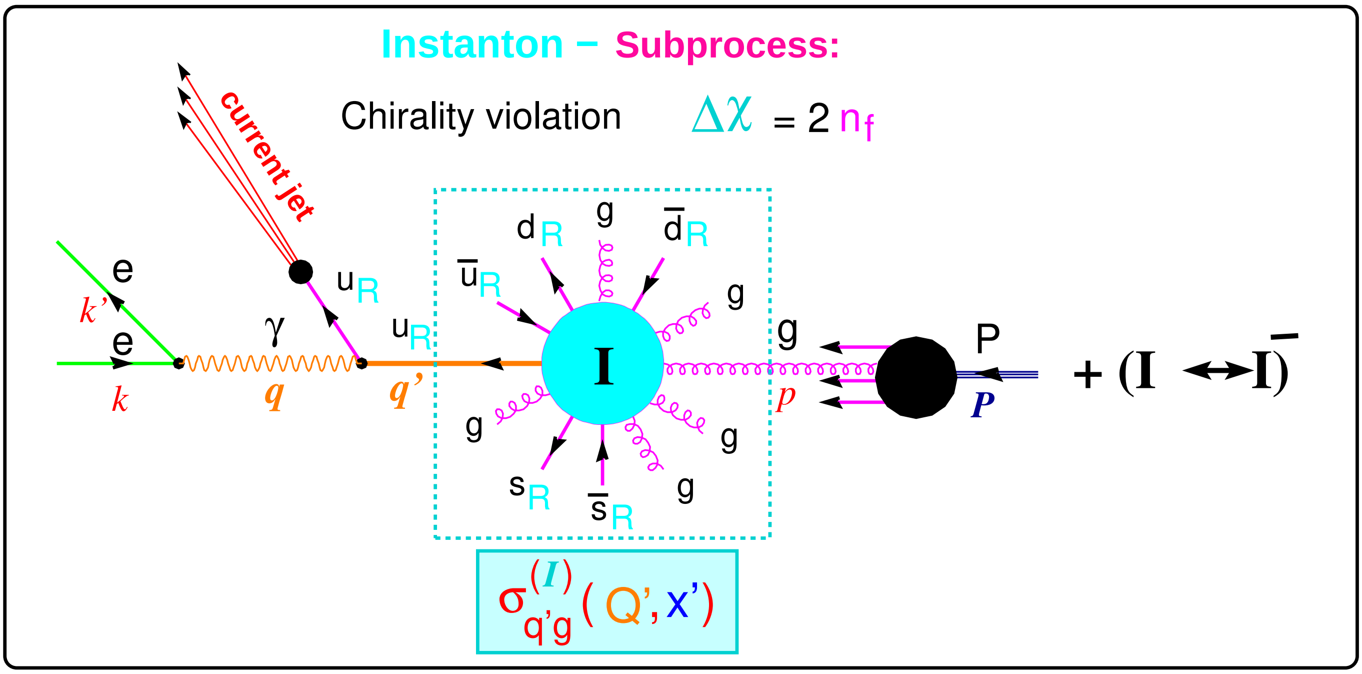
⇒ important support for basic prerequisites of our calculations in **DIS**, "fiducial" kinematical region. . .
[Ringwald & F. Sch., Phys. Lett. **B 438** (1998) 217, **B 459** (1999) 249]

2. Instanton Perturbation Theory in Deep-Inelastic Scattering

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

- $\boldsymbol{I}$-perturbation theory — for dilute gas of $\boldsymbol{I}$'s and $\overline{\boldsymbol{I}}$'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 $\boldsymbol{I}$-solution $A_\mu(x) = A_\mu^{(\boldsymbol{I})}(x) + \cdots$ 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 **deep-inelastic** regime of $e^{\pm}$P scattering:



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

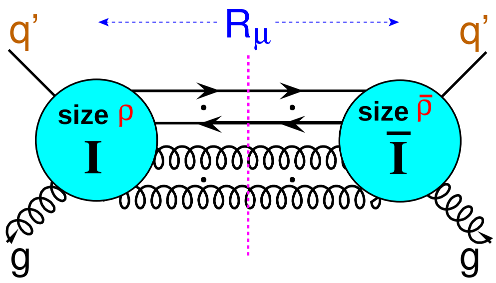
$$\text{large} \quad Q'^{\,2} = -q'^{\,2} > 0; \quad x' = \frac{Q'^{\,2}}{2p\cdot q'} \leq 1 \quad \text{fixed}$$

- Factorization in $\boldsymbol{I}$-perturbation theory (Bjorken limit):

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

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

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

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

- 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

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

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

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

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

$d =$ 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 $\rho, \overline{\rho} \lesssim 1/Q'$

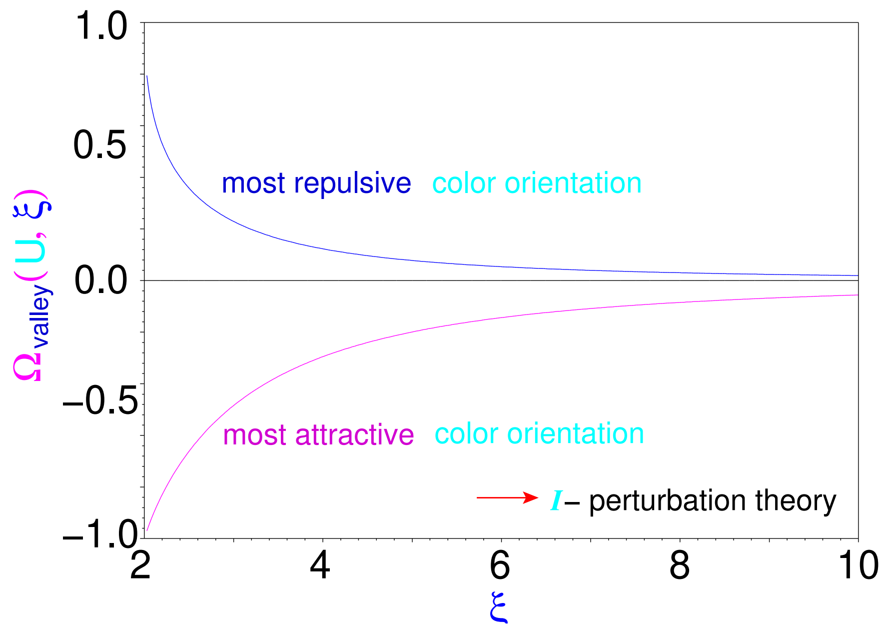
$\diamondsuit$ $\Omega\left(U, \frac{R^2}{\rho\overline{\rho}}, \frac{\overline{\rho}}{\rho}\right)$

- within I-perturbation theory: known as series for $\boxed{R^2/\rho\overline{\rho} \gg 1}$;
- 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

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

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

◇ $\Rightarrow$ formally, for large Q' and small $(1-x')$:

dilute gas ($R/\rho \gg 1$) of small $\boldsymbol{I}$'s and $\overline{\boldsymbol{I}}$'s ($\rho \sim 1/Q'$)!

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

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

◇ **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 $\boldsymbol{I}$-coordinates

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

Region of Validity of the Predictions

[Ringwald & F. Sch., Phys. Lett. **B 459** (1999) 249; **B 438** (1998) 217, hep-ph/0012241]

◇ Region of validity of I-perturbation theory in (Q', x') from re-analysis of recent high-quality lattice 'data' for $\mathrm{QCD}_{\mathrm{n_f=0}}$ [UKQCD, Smith & Teper, '98]

♣ ≈ **parameter-free** comparison of I-size and $I\bar{I}$-distance distributions with I-perturbation theory versus $(\rho,\ R)$:

♣ QCD -scale for $n_f = 0$ with small error also from lattice:

$$\Lambda_{\overline{\mathrm{MS}}}^{(n_f=0)} = (238 \pm 19)\ \mathrm{MeV}$$

[ALPHA-Collaboration, Nucl. Phys **B 544** (1999) 669]

♣ **Results:** I-perturbation theory quantitatively valid for

$$\left.\begin{array}{lll} \rho \cdot \Lambda_{\overline{\mathrm{MS}}}^{(n_f=0)} & \lesssim & 0.42 \\ R/\rho & \gtrsim & 1.05 \end{array}\right\} \overset{\textbf{saddle pt}}{\Rightarrow} \left\{\begin{array}{lll} Q'/\Lambda_{\overline{\mathrm{MS}}}^{(n_f)} & \gtrsim & 30.8, \\ x' & \gtrsim & 0.35, \end{array}\right.$$

- Good **agreement** of lattice results with I-perturbation theory very interesting by itself!
- Analysis of uncertainties ⇒ [Ringwald & F. Sch., hep-ph/0012241]
- **Illustration of agreement:** ⇒

I-Size Distribution:

$$\frac{d\, n_{I+\bar{I}}}{d^4x\, d\rho}\Big|_{\mathbf{UKQCD}} \overset{?}{\simeq} 2\, \boxed{D(\rho)}\Big|_{I-\text{pert. theory}}$$

Parameter-free **agreement** in shape and normalization, for $\rho \cdot \Lambda_{\overline{\mathrm{MS}}}^{(n_f=0)} \lesssim 0.42$

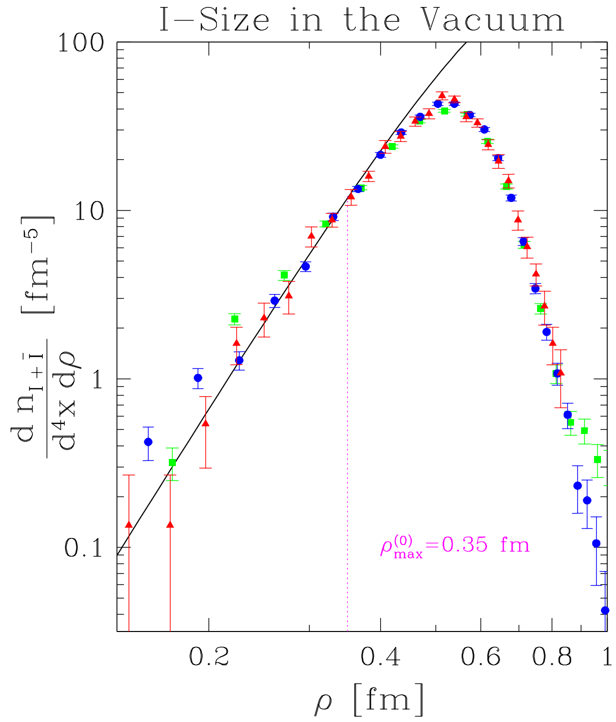
Almost independent of μ_r for large range of μ_r (2-loop RG-invariance!)

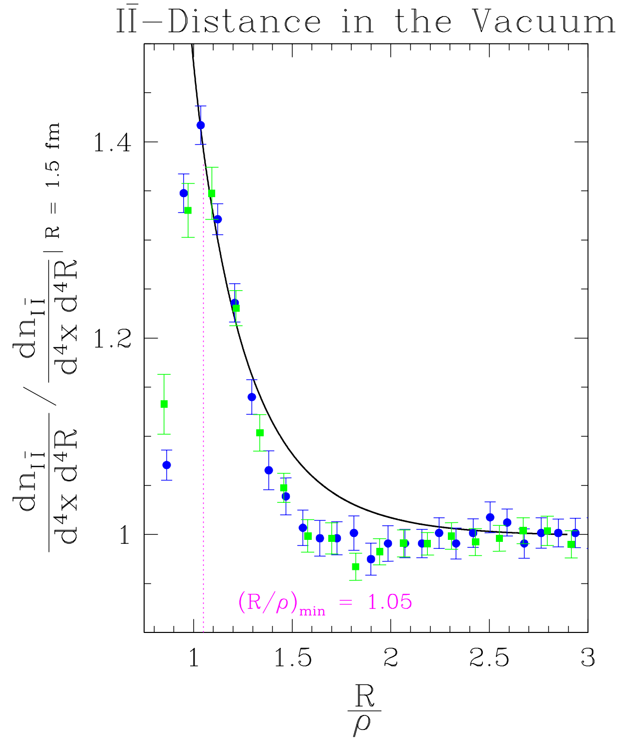
$I\bar{I}$-Distance Distribution:

$$\frac{d\, n_{I\bar{I}}}{d^4x\, d^4R}\Big|_{\mathbf{UKQCD}} \overset{?}{\simeq} N \int_0^\infty d\rho \int_0^\infty d\bar{\rho}\, \boxed{D(\rho)\, D(\bar{\rho})}$$

$$\times \int dU\, \mathrm{e}^{-\frac{4\pi}{\alpha} \boxed{\Omega_{\text{valley}}\left(U, \frac{R^2}{\rho\bar{\rho}}, \frac{\bar{\rho}}{\rho}\right)}}$$

Good **agreement** with Ω_{valley} for $R/\rho \gtrsim 1.05$, using $D(\rho)$ from lattice





Exploitation of **lattice results** increases the reliability of our theoretical predictions for **HERA** dramatically!

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,. . . [F. Sch & A. Utermann, in progress]

Must require: $\boxed{\text{additional cut in } Q^2\text{:}}$ $Q^2_{\min} \approx Q'^2_{\min}$

- Assures dominance of "planar" (handbag-type) graphs in $\sigma^{(I)}{}_{\rm HERA}$ and final-state observables;
- Non-planar contributions involve $\boldsymbol{I}$'s of size $\sim 1/Q$ rather than $\sim 1/Q'$
- hard to calculate and hard to implement in Monte Carlo

Known $1/Q^2$ suppression and a cross-check in simplest process without final-state gluons $\Rightarrow$ Non-planar contributions small, provided $Q^2 > Q^2_{\min} \approx Q'^2_{\min} \Rightarrow$ ignored!

3. Rate and Final-State Signatures

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

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

Known Uncertainties?

- Where to place exactly the (Q', x')-cuts? $\Leftarrow$ Lattice!

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

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

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

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

lattice: $Q'_{\rm min} \propto \Lambda_{\overline{\rm MS}} \Rightarrow$ 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

♣ $\Rightarrow$ Upgraded, I-induced **HERA** cross section:

$$\sigma^{(I)}{}_{\rm HERA}(\mathcal{C}_{std}) = 29.2\,^{+9.9}_{-8.1}\ \text{pb},$$

with much reduced known uncertainties!

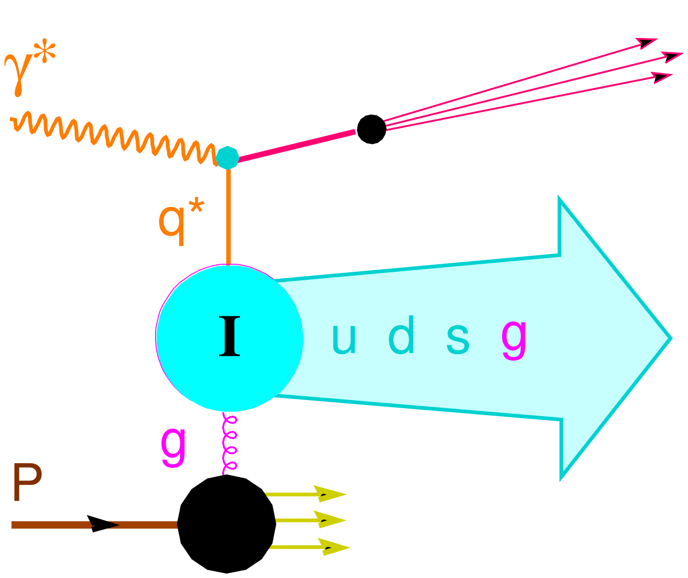
H1 $\bigoplus$ **ZEUS**: $\int_{1996}^{2000} \mathcal{L} dt = 2\,\mathcal{O}(75)\ \text{pb}^{-1}, \Rightarrow$

$\mathcal{O}(4350)$ I-induced events within region of validity of I-perturbation theory on tape **!?**

Characteristic Final-State Signature

Indispensable Tool: Monte-Carlo generator package for simulation of instanton events at **HERA**:

"QCDINS 2.0" [Gibbs, Ringwald & F. Sch. '95,
Ringwald & F. Sch, Comp. Phys. Com. **132** (2000) 267 (**long-wite-up**);
WEB: http://www.desy.de/∼t00fri/qcdins/qcdins.html]

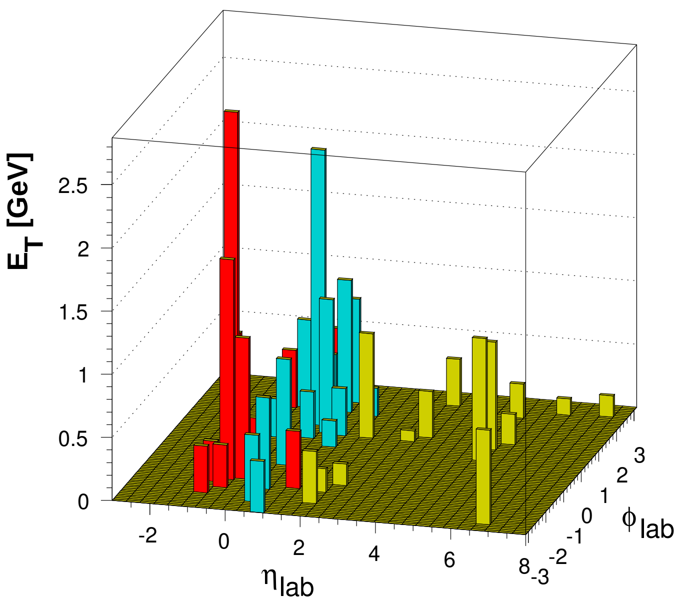


- current jet
- "band"-region: ⇔

In I-rest system: "Fireball" decaying **isotropically** into

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

$\mathcal{O}(10)$ partons



◇ Large total E_t
◇ Large multiplicity
◇ "u, d, s flavour democracy":
Strangeness ⇒ $K's, \Lambda's$
◇ No further jets

4. First Dedicated Search Results (H1)

[S. Mikocki for H1-Collaboration, *DIS2000*, Liverpool 25.-30. April 2000; H1-Collaboration, *ICHEP2000*, Osaka, July 2000, www-h1.desy.de/psfiles/confpap/ICHEP2000/H1prelim-00-025.ps]

Search Strategy and Observables

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

- Isolation of "$\boldsymbol{I}$-enriched data" by means of cuts to a set of most $\boldsymbol{I}$-sensitive observables. Place cuts such as to maximize

  $$\boldsymbol{I}\text{-separation power} = \frac{\epsilon_I}{\epsilon_{\mathrm{nDIS}}}$$

  in terms of efficiencies $\epsilon_I > 10\%$ and ϵ_{nDIS} for instanton and normal DIS events, respectively ($\Leftarrow$ **MC**-generators).

- For individual observables, $\boldsymbol{I}$-separation power $\lesssim \mathcal{O}(20)$! $\Rightarrow$

- **Multi**-observable analysis required. E.g. set of " 3 best" (among ~ 30) increase $\boldsymbol{I}$-separation power to $\mathcal{O}(90)$!

- Work mostly in "hadronic CMS" ($\vec{\gamma}^* + \vec{P} = 0$).

- **"Current jet"**: $\Leftrightarrow$ Jet with largest Et, via 'cone'-algorithm.

- 3 $\boldsymbol{I}$-sensitive observables with $\boldsymbol{I}$-optimized cuts:

$n_{ch,\,b}$	number of charged hadrons in $\boldsymbol{I}$- "band" region
Sph	sphericity in rest system of "non-jet"-particles
$Q'^{\,2}_{\rm rec}$	reconstructed virtuality of $\boldsymbol{I}$-subprocess quark q'

- 3 further $\boldsymbol{I}$-sensitive observables without additional cuts:

Et_b	total transverse energy in $\boldsymbol{I}$- "band" region
Δ_b	Et-weighted azimuthal-isotropy
$Et_{\rm jet}$	transverse energy of 'current-jet'

Data vs. Theory and Main Uncertainties

[Ringwald & F. Sch., hep-ph/0012241]

- 1997 data only: $\int \mathcal{L}dt = 15.78\,\mathrm{pb}^{-1}$; $2.8\,10^5$ used events.

- **nDIS**: Two different Monte-Carlo's (**uncertainties!**)

$$\left\{ \begin{array}{l} \textbf{CDM} = \text{"Color Dipole Model" } (\Rightarrow \text{ARIADNE}) \text{ and} \\ \textbf{MEPS} \ (\Rightarrow \text{RAPGAP}) \end{array} \right\}$$

- **3 cut scenarios: A), B), C)**:
  $\Leftrightarrow$ increasing $\boldsymbol{I}$-separation power ($\Leftarrow$ **MC** generators), focussing on basic characteristics of $\boldsymbol{I}$-induced events!

- **Caveat: H1** data sample has **no** x'-cut and **no** Q^2-cut.

- **H1** compared data to our predictions from **QCDINS MC** **with default x'-cut**, $x' \geq 0.35$, and **without Q^2-cut** $\Rightarrow$

- Implications:

  $\triangledown$ **Missing x'-cut in data:** Not too bad, since

  QCDINS($x' \geq 0.35$) $\Leftrightarrow$ model for sharp suppression of $\boldsymbol{I}$-effects, in lattice data of $\boldsymbol{I\bar{I}}$-distance distribution for $R/\rho \lesssim 1.0 - 1.05$, i.e. $x' \lesssim 0.3 - 0.35$ (Fig.)!

  $\triangledown$ **Missing Q^2-cut:** expect incorrect **QCDINS** results, for distributions that are very sensitive to low-Q^2 spectrum ($\Leftrightarrow$ missing non-planar graphs, too big $\boldsymbol{I}$'s of size $\sim 1/Q$):

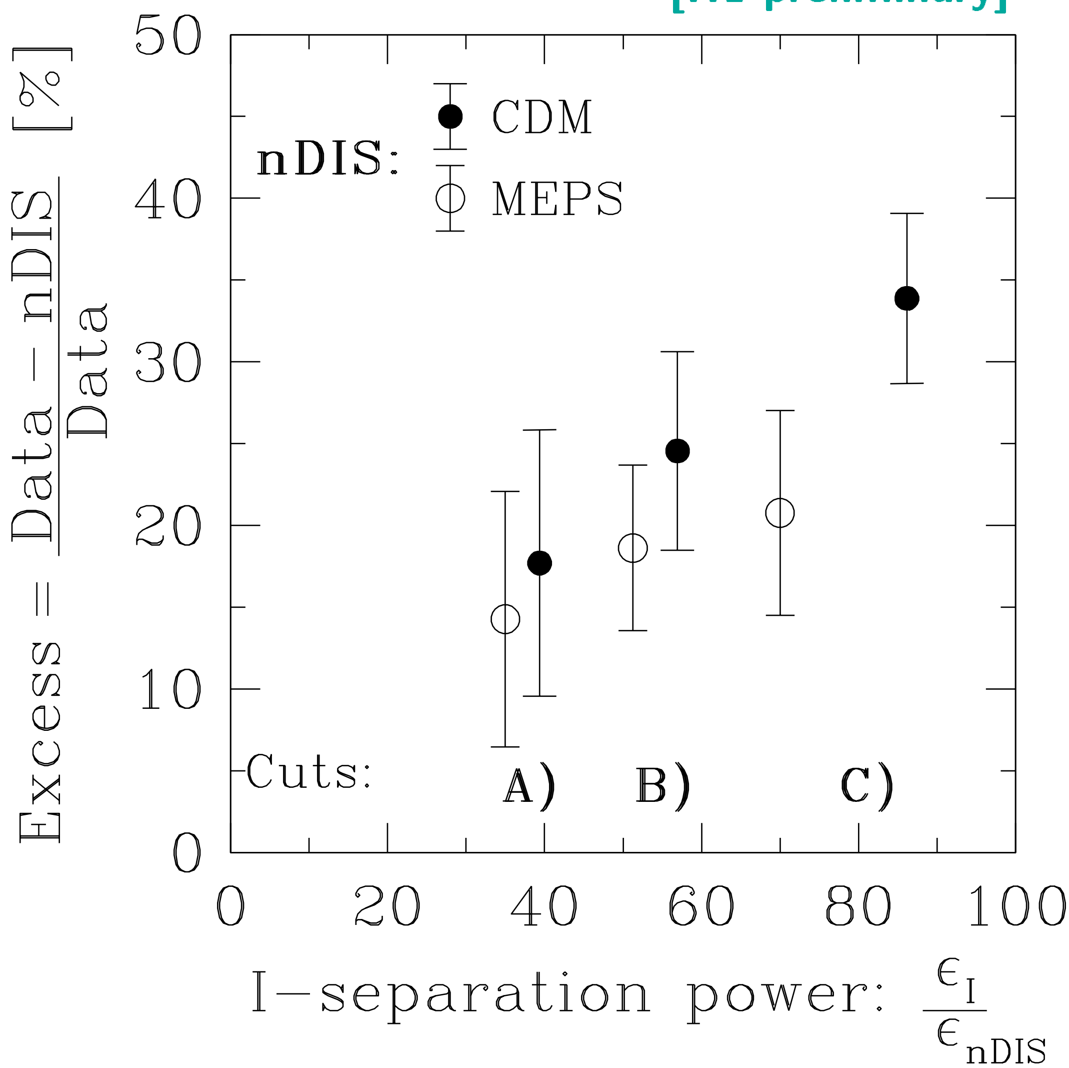
  $\langle \boldsymbol{Et}_{\rm jet} \rangle$ and $\langle \boldsymbol{Et}_b \rangle$ **too large** (see later).

Despite these warnings . . .

♣ Intriguing and encouraging observations by **H1**:

Significant excess, increasing with I-separation power!

[H1 preliminary]

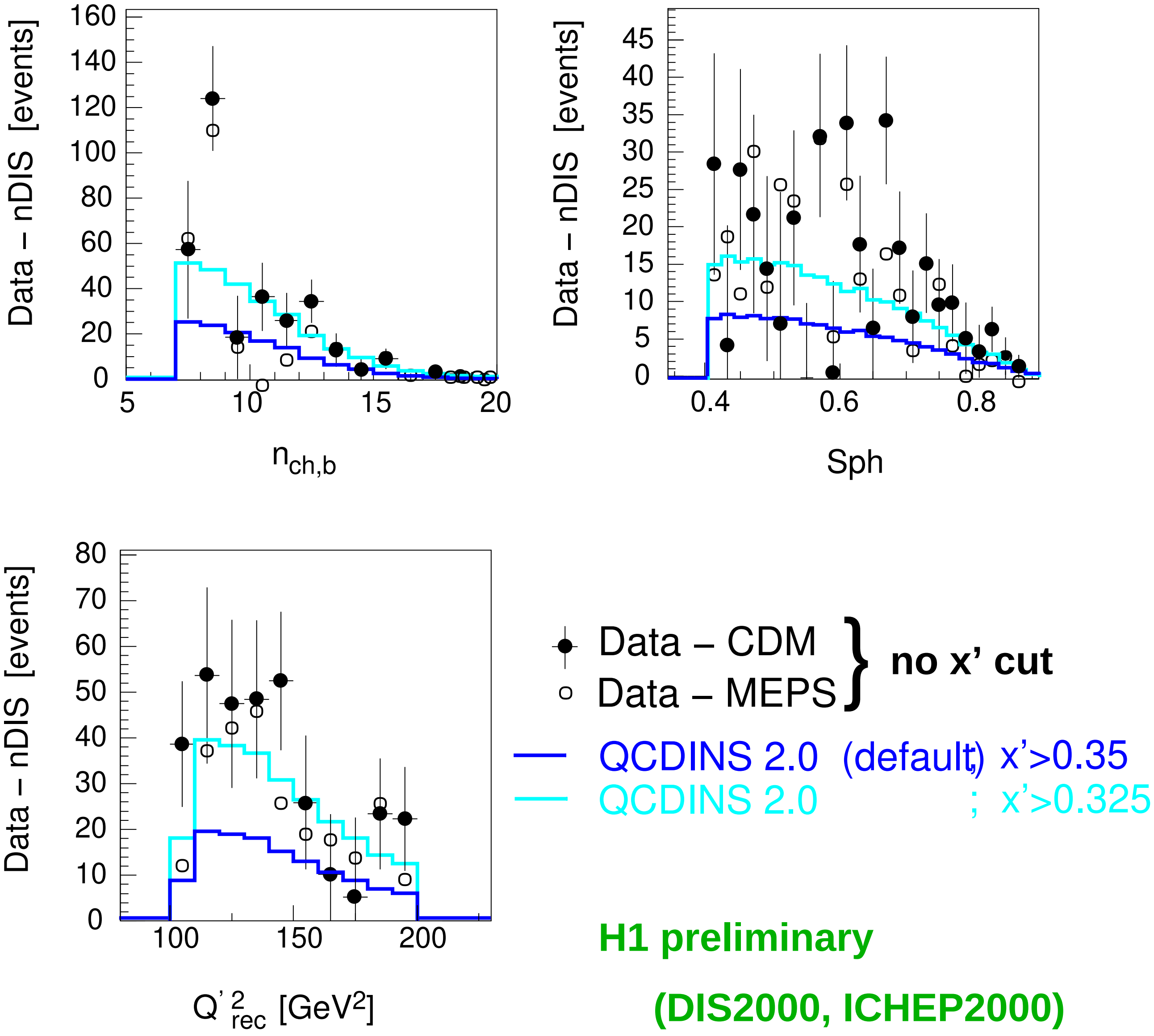


Still in progress: Search for $K^{\pm}$**-excess** (dE/dx) in the same I-enhanced **H1**-data sample.

Crucial, independent signature, due to (light) flavour democracy for I-events

- **3** discriminating observables with optimized cuts:

Cuts B): 1332 events; excess: $\begin{cases} 327^{+82}_{-70} & \text{CDM} \\ 248^{+75}_{-46} & \text{MEPS} \end{cases}$

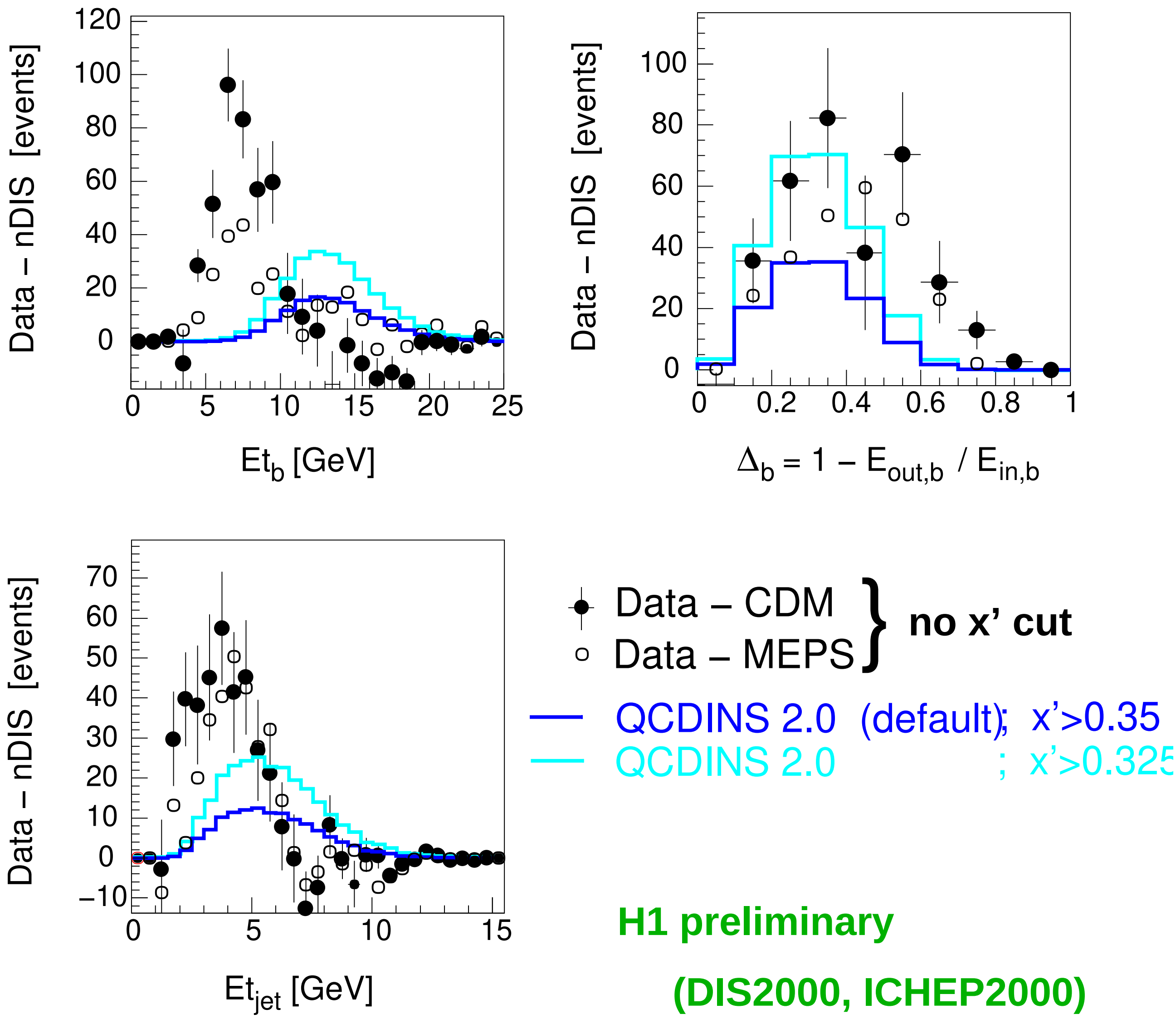


- Qualitatively similar excess for the 2 different **nDIS** Monte-Carlo's considered!

- Small decrease of fiducial x'-cut (well compatible with lattice data!) improves agreement considerably.

- **3** further observables without additional cuts:

Cuts B): 1332 events; excess: $\begin{cases} 327^{+82}_{-70} & \text{CDM} \\ 248^{+75}_{-46} & \text{MEPS} \end{cases}$



- Event-shape observable Δ_b agrees quite well, too.

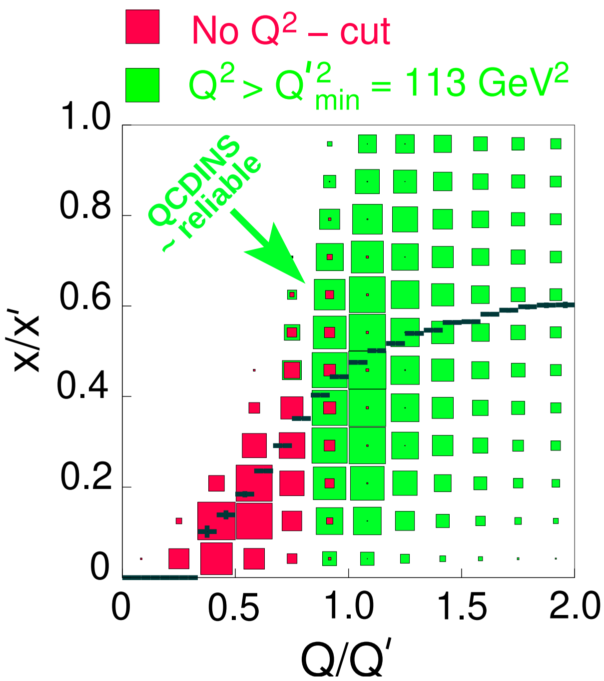
Relation of shift in $\langle Et_{\rm jet}\rangle$ and $\langle Et_b\rangle$ to missing Q^2-cut:

E.g. for $Et_{\rm jet}$, simple formula (parton level, hadr. CMS):

$$Et_{\rm jet} = Q'\sqrt{1-\frac{x}{x'}}\sqrt{1-\frac{x}{x'}\left(\frac{Q'}{Q}\right)^2}, \qquad (*)$$

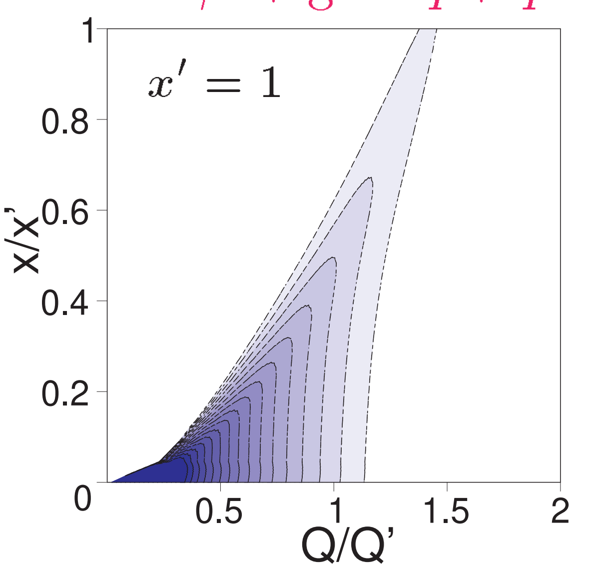
with $x = Q^2/2p\,q$ = Bjorken - x of $\gamma^*(\,q\,) + g(\,p\,) \Rightarrow X$

Note: $Et_{\rm jet}$-distribution $\Leftrightarrow$ $\frac{x}{x'}$ and $\frac{Q}{Q'}$-distributions (Fig.)



Non-planar/planar > 1

in $\gamma^* + {\rm g} \overset{(\mathbf{I})}{\Rightarrow} q + \overline{q}$



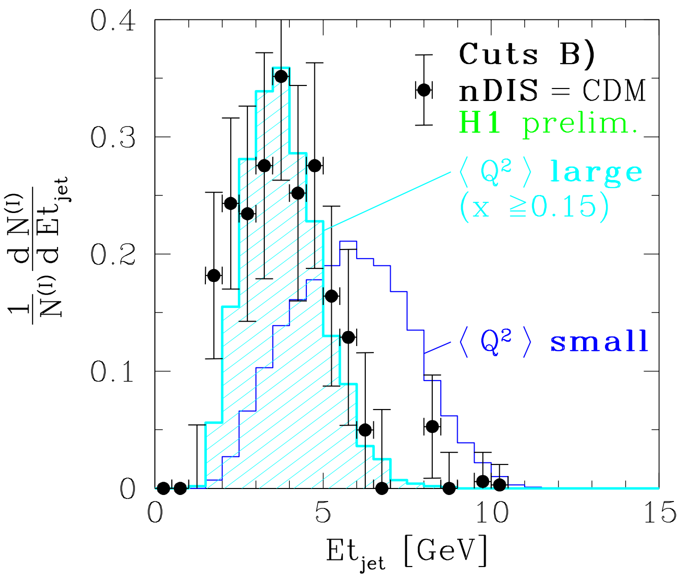
- **no Q^2-cut:** small $\langle\frac{Q}{Q'}\rangle \approx 0.4$, **tiny** $\langle\frac{x}{x'}\rangle \approx 0.12$ (Fig. left)

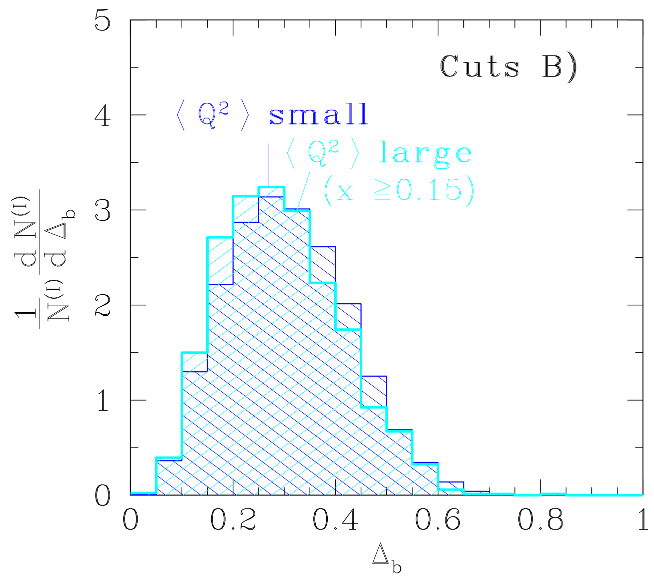
$\overset{(*)}{\Rightarrow}$ $\langle Et_{\rm jet}\rangle \approx 6$ GeV, **too large** compared to **H1**-excess.

- **Reason:** **Non-planar** contributions, lacking in **QCDINS**, are largest here! C. f. calculable $\gamma^* + {\rm g} \overset{(\mathbf{I})}{\Rightarrow} q + \overline{q}$ (Fig. right)

- **Expect:** Additional events due to non-planar graphs, to increase $\langle x/x'\rangle$ for $Q/Q' < 1 \Rightarrow \langle Et_{\rm jet}\rangle$ **smaller**!

- Model by depleting low $\frac{x}{x'}$ with a cut: $x \geq 0.43\, x'_{\rm min} = 0.15$, $\Rightarrow$ **QCDINS** now $\approx$ reliable, since $\langle Q^2 \rangle \approx 95$ GeV^2 $\Rightarrow$





- $Et_{\rm jet}$-peak left-shifted to $\langle Et_{\rm jet} \rangle \approx 3.5$ GeV and narrower, in good agreement with shape-normalized **H1**-excess!

- Analogously for Et_b!

- Shape of other **4** observables $\approx$ unaffected by $x > 0.15$ cut (Fig.), hence insensitive to missing non-planar effects.

♣ Intriguing qualitative overall agreement and much improved understanding . . .

♣ Both Q^2-cut and x'-cut **can** and **should** be implemented experimentally. $\Rightarrow$ Strong reduction of remaining (size-)ambiguities!

- Remaining problematics: Excess based on **MC** for **nDIS**. I-signal where **nDIS** not too well known . . .

5. Conclusions

- Instantons, as non-perturbative, topological fluctuations of the gluon fields, are an essential aspect of QCD
- Tunnelling transitions, signalled by existence of characteristic, hard processes with chirality violation.
- Discovery of $\boldsymbol{I}$-events would be of fundamental significance.
- **HERA** offere a unique opportunity in **DIS**
- Systematic theoretical and phenomenological investigation of the "discovery potential":

  calculable rate in measurable range; event signature!
- Intriguing results from first dedicated $\boldsymbol{I}$-search [**H1**, preliminary]:
  - significant excess compared to **nDIS** Monte-Carlo's, increasing with $\boldsymbol{I}$-separation power.
  - qualitative similarity with form of instanton-prediction for most of the 6 considered observables;
  - size in the required ballpark with default cuts and $\Lambda_{\overline{\mathrm{MS}}}$;
  - Improved understanding of agreement and apparent disagreement, while Q^2- and x'-cuts still lacking in data.
- **"Es wird spannend. . . "**