Signatures of Instanton-Induced Processes

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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**

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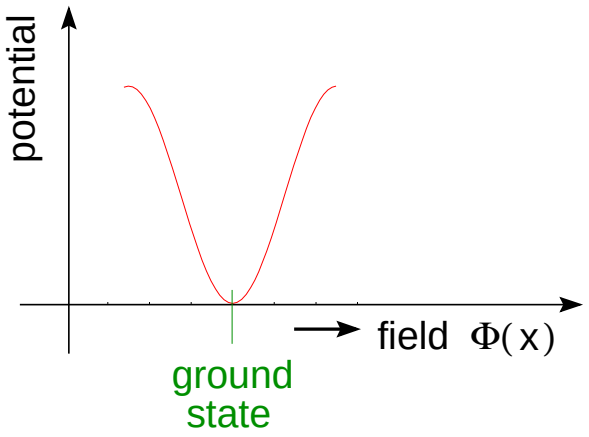
http://www.desy.de/~t00fri/talks/talks.html

– ZEUS Collaboration Meeting, DESY, June 24th, 1999 –

1. Instantons

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

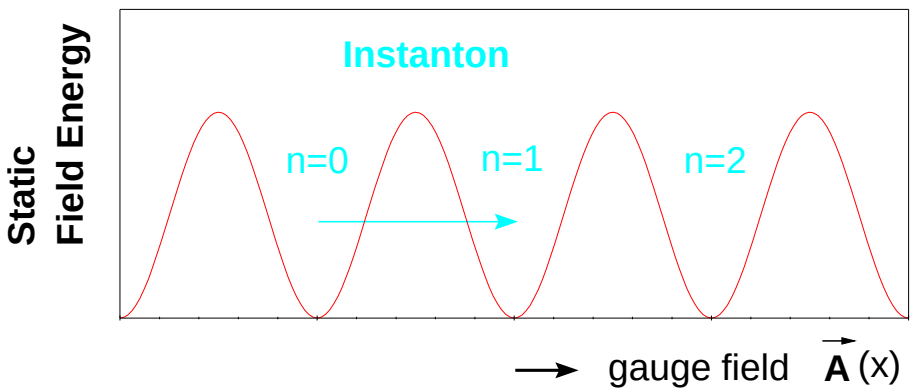
Generic picture:



Local gauge invariance of QCD

Non-abelian structure of color gauge group

- Gauge fields $A_\mu(x) \Leftrightarrow$ topologically non-trivial boundary conditions for $|x| \to \infty$, $\Rightarrow$ carry conserved topological charge $Q = n - n_0$, integer winding number n
- Classically: infinitely many energetically degenerate, but topologically distinct ground states with finite action

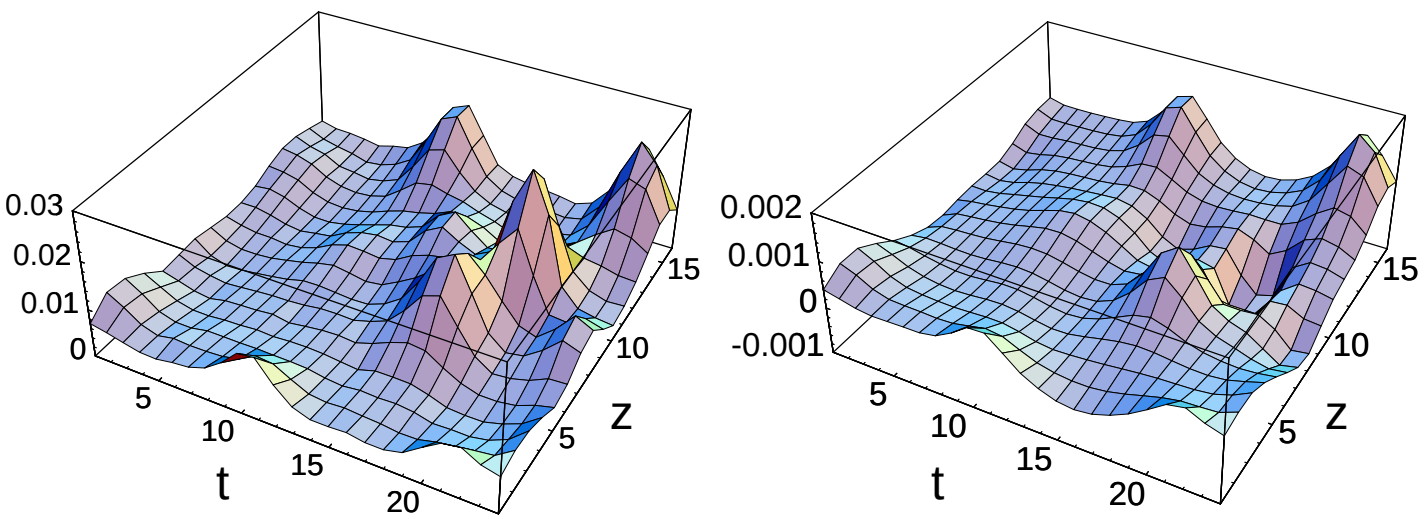


♣ **Instantons (I)** and **anti-instantons ($\overline{I}$)**: [Belavin *et al.* '75, 't Hooft '76]

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

◇ Non-perturbative 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 $\overline{I}$'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 $|\ Q\ | = 1$: $S[A_\mu^{(I)}(x)] = \frac{2\pi}{\alpha}$.

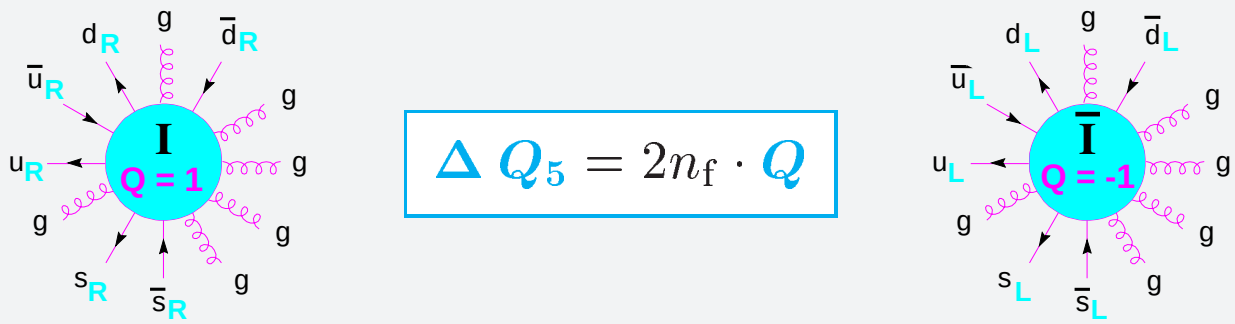
- Instantons widely believed to play an important rôle in various long-distance aspects of (full) QCD :

  – 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" $Q_5 = \#(q_{\rm R}) - \#(q_{\rm L})$ in QCD with $\approx$ massless quarks ['t Hooft '76]

♣



  – 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 $\Leftarrow$ **HERA !**.

♣ **DIS** regime at **HERA** offers unique discovery window for events induced by QCD -instantons, through

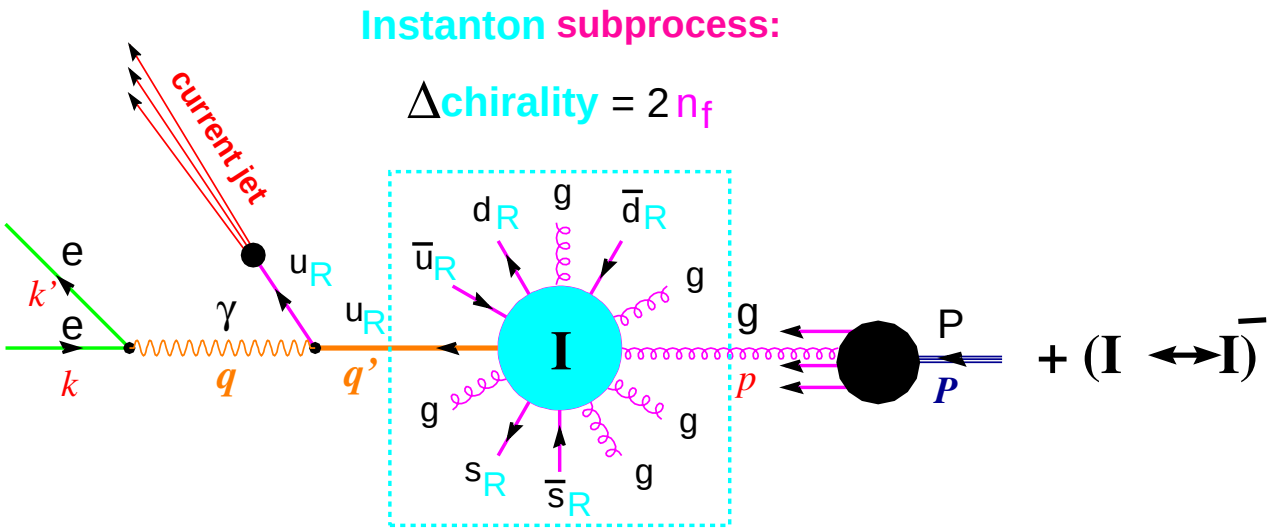
♢ their characteristic final-state signature
[Ringwald & F. Sch. '94 - '99, Carli, Gerigk, Ringwald & F. Sch. '99]

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



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

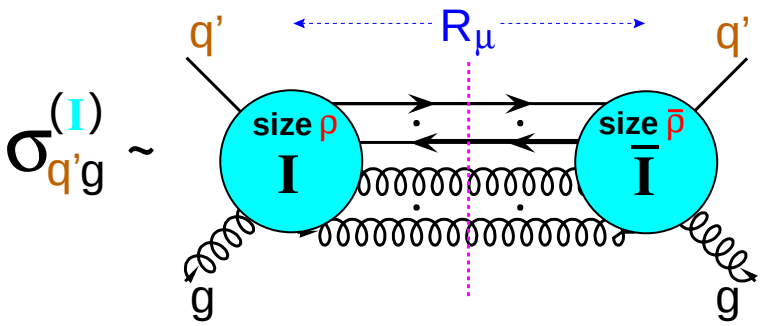
$$\text{large} \quad Q'^2 = -q'^2 > 0; \quad x' = \frac{Q'^2}{2p\cdot q'} \leq 1 \quad \text{fixed}$$

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

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

- Differential luminosity, $\mathrm{d}\mathcal{L}^{(I)}_{q'g}$: 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 I-background.

- Crucial I-dynamics in total cross-section $\sigma^{(I)}_{q'g}(Q', x')$ of I-subprocess $q'g \overset{I}{\Rightarrow} X$!



- Being an observable, $\sigma^{(I)}_{q'g}(Q', x')$ involves **integrations** over all I and $\overline{I}$-"collective coordinates",

$$I\text{-size } \rho,\ \overline{I}\text{-size } \overline{\rho},\ I\overline{I}\text{-distance 4-vector } R_\mu,$$
$$\text{and} \quad U{=}I\overline{I} \text{ relative color orientation}$$

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

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

- 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 $\boldsymbol{I}$-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 $\boldsymbol{I}$-perturbation theory, since $\boldsymbol{I}$-size integrals diverge for large ρ (infrared)

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

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

- known as series for $R^2/\rho\overline{\rho} \gg 1$
- analytically known within "$I\overline{I}$-valley" approximation [Yung '88, Khoze & Ringwald '91, Verbaarschot '91]

"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**]

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

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

♢ Link between **DIS** and **lattice** observables!

♢ **Lattice** $\Rightarrow$ Independent, non-perturbative information on range of validity of their predicted form in (R, ρ)

♢ Crucial one-to-one [saddle-point] correspondence of effective I-coordinates $(R^*, \rho^*) \Leftrightarrow$ **DIS** var's (x', Q')

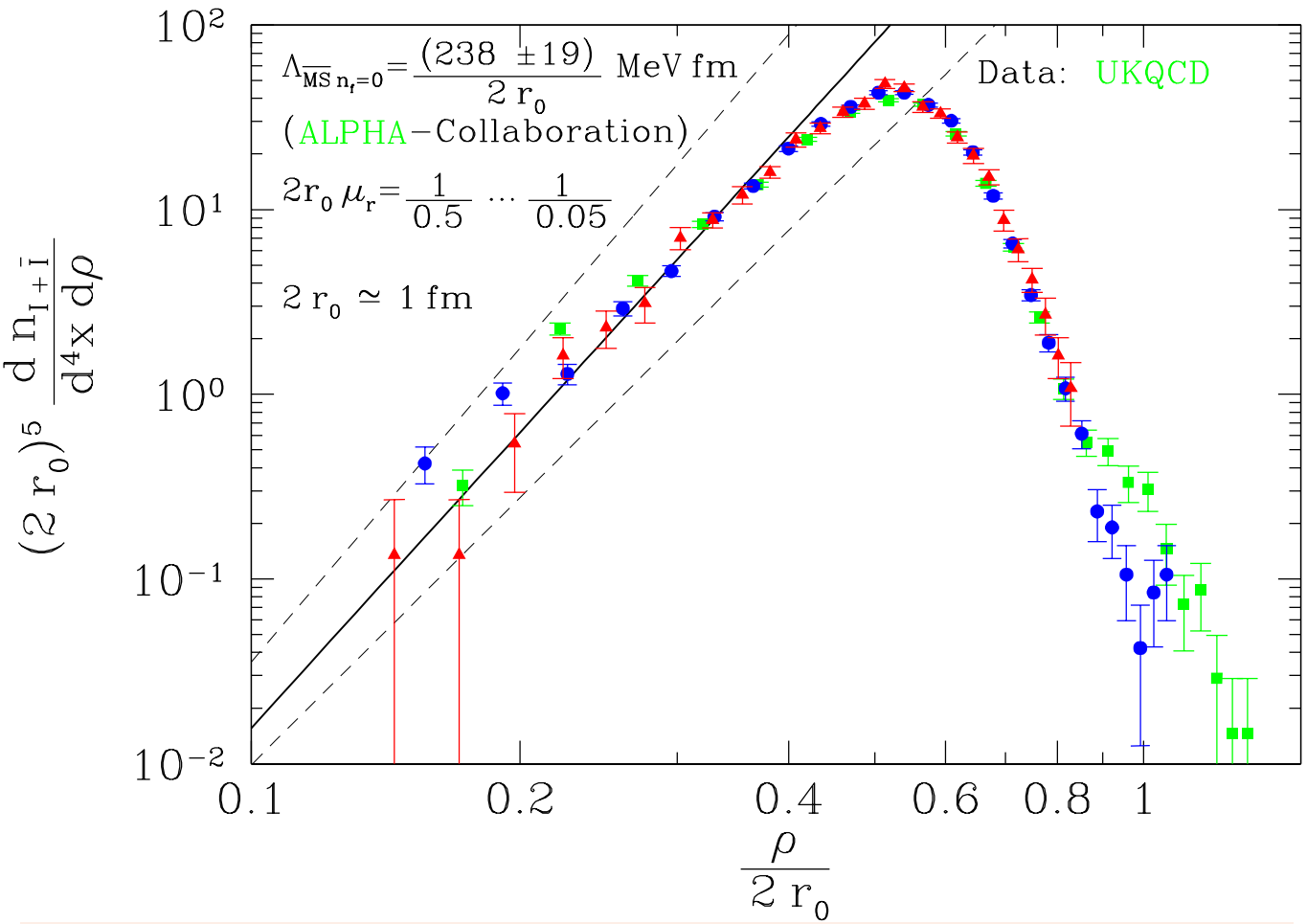
$$\rho^*\Lambda = \overline{\rho}^*\Lambda \sim \frac{4\pi}{\alpha}\frac{\Lambda}{Q'} = \text{function}(\frac{Q'}{\Lambda}) \qquad \frac{R^*}{\rho^*} \sim 2\sqrt{\frac{x'}{1-x'}}$$

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

- Exploit recent high-quality **lattice** simulation of $\mathrm{QCD}_{\,\mathrm{n_f}=0}$ [UKQCD, Smith & Teper, '98,. . .]

- 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]

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

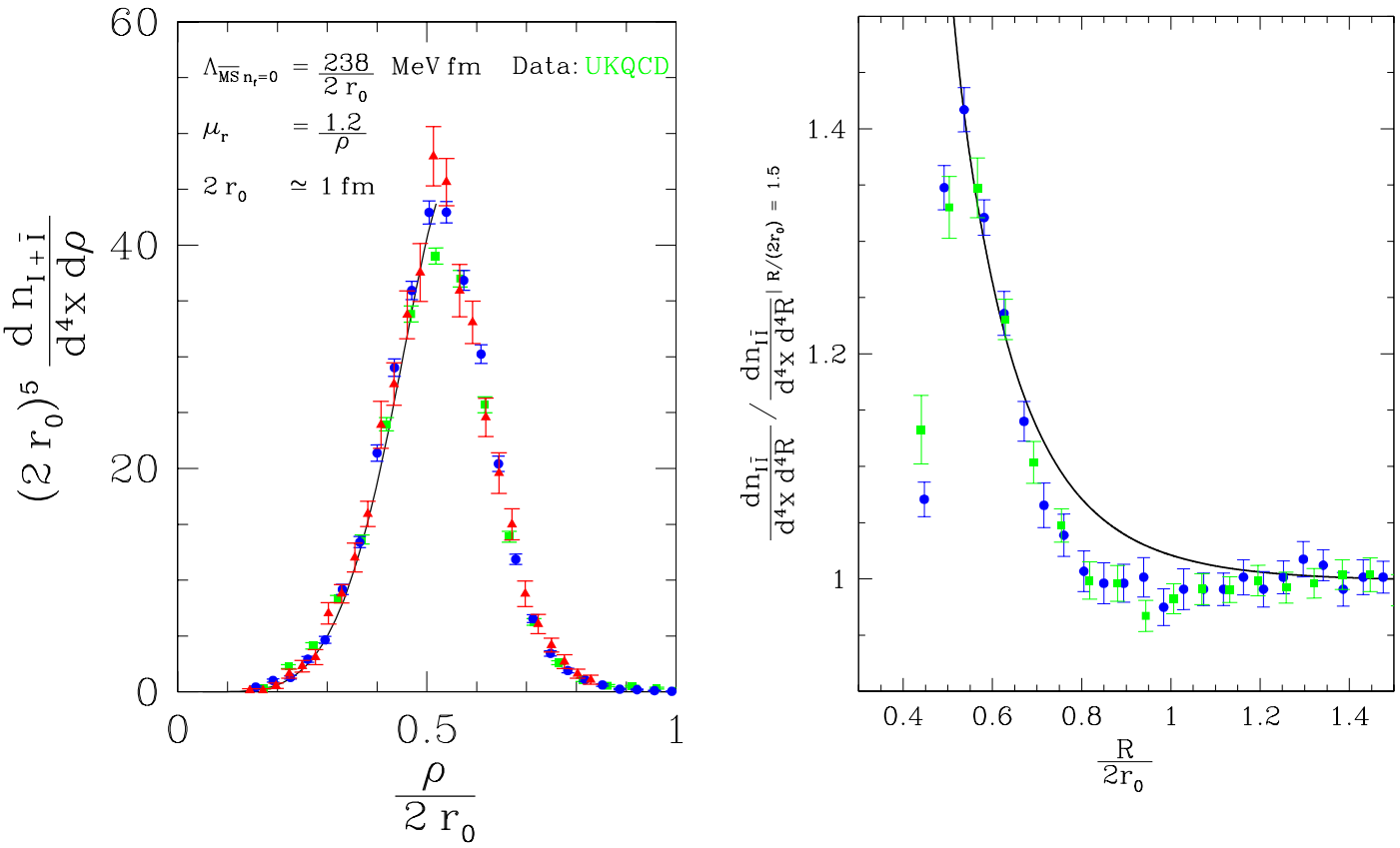


⇒ Parameter-free **agreement** in shape and normalization,

for $\rho \lesssim 0.30 - 0.36$ 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]

- **Improved choice:** $\mu_r \rho = \mathcal{O}(1)$, to minimize $\ln(\mu_r \rho)$-corrections $\Rightarrow$ **agreement** up to the peak, $\rho \lesssim 0.5$ fm (Fig.)!



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

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

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

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

DIS:

$$\left.\begin{array}{lcl} \rho & \lesssim & 0.3 \text{ fm} \\ R/\rho & \gtrsim & 1 \end{array}\right\} \Rightarrow \left\{\begin{array}{lcl} Q'/\Lambda & \gtrsim & 28.3 \\ x' & \gtrsim & 0.35. \end{array}\right.$$

♢ Promising: Try replacing $D(\rho)$ and $I\overline{I}$-interaction Ω by the actual form measured on the lattice! ⇒ **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?

- $\sigma^{(I)}{}_{\rm HERA}$ steep function of (x', Q') cuts, but uncertainties much reduced by **lattice** results!

♢ Strong dependence of $\sigma^{(I)}_{\mathbf{HERA}}$ on error of $\Lambda_{\overline{\rm MS}}$ via,

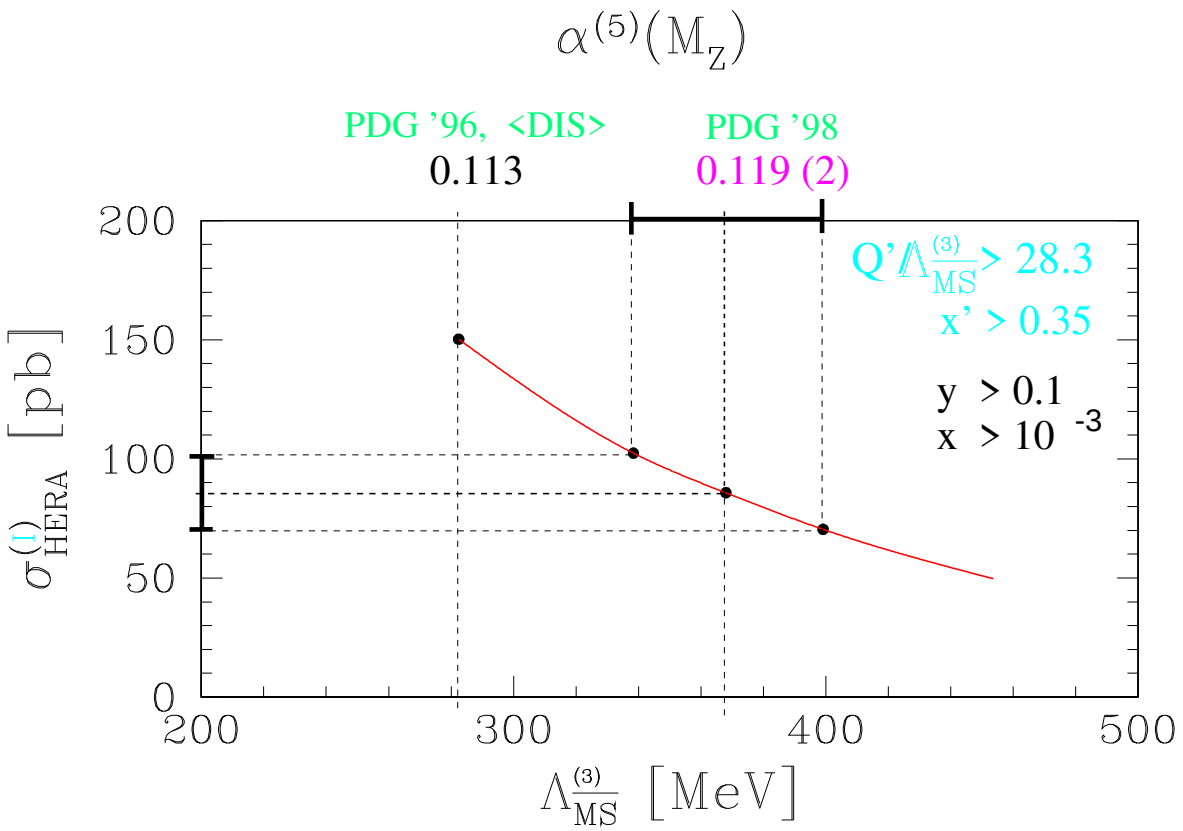
$$Q'^{\,2}\,\sigma^{(\boldsymbol{I})}_{q^*g} \propto \mathrm{e}^{-\frac{4\pi}{\alpha(Q')}(\Omega^*(x')+1)} \simeq \left(\frac{\Lambda_{\overline{\rm MS}}}{Q'}\right)^{2\beta 0\,(\Omega^*(x')+1)}$$

Published: [Ringwald & F. Sch., Phys. Lett **B438** (1998) 217], with **DIS** average for $\Lambda^{(3)}_{\overline{\rm MS}}$ from PDG '96,

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

for $\Lambda^{(3)}_{\overline{\rm MS}}$-independent "standard" cuts $\mathcal{C}_{\rm std}$ ($\Leftarrow$lattice!)

♣ Much weaker $\Lambda_{\overline{\rm MS}}$-dependence for proper $\Lambda_{\overline{\rm MS}}$-dependent Q'-cuts ($\Leftarrow$ lattice!) and upgrade to PDG '98 world-average:



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

$\mathcal{O}(6500)$ I-induced events on tape **!?**

3. Signatures and Searches at HERA

QCDINS

♣ Important tool: "QCDINS 1.6 $\Rightarrow$ 1.7β" [theopc3.desy.de]

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

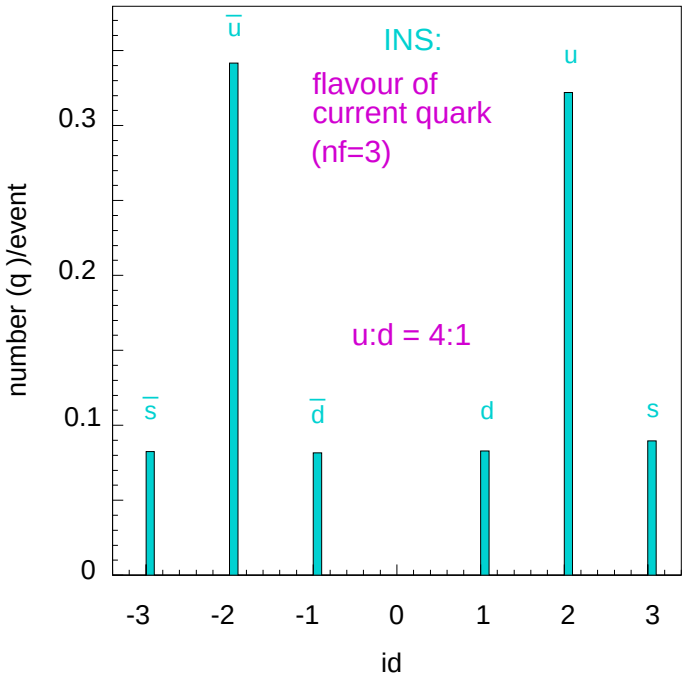
[Gibbs, Ringwald & F. Sch. '95; Ringwald & F. Sch. to appear]

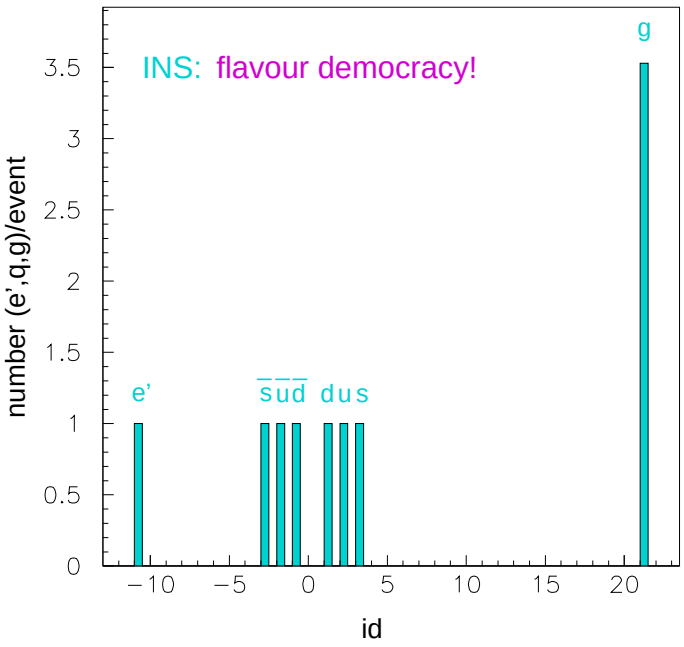
♢ I-induced hard subprocess with essential characteristics derived theoretically:

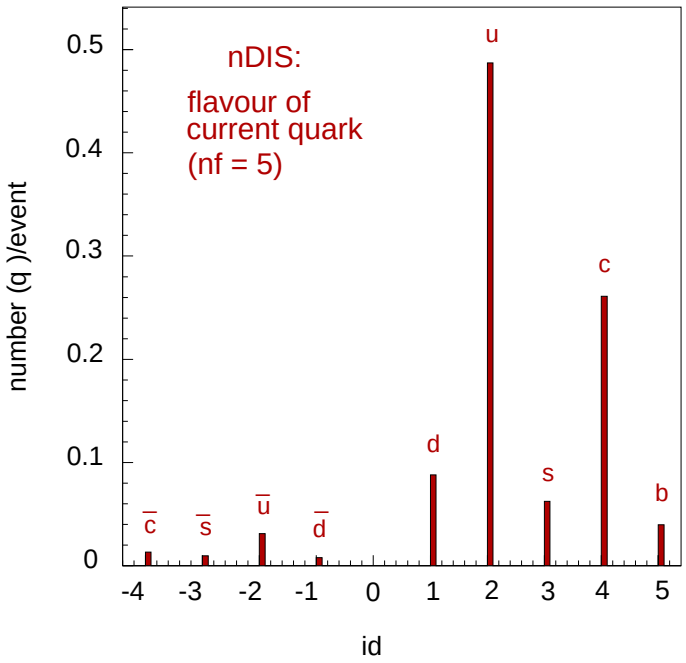
- isotropic production of partonic final state in CMS of I-subprocess ("fireball")
- flavour "democracy"
- energy weight factors different for quarks and gluons
- large $\langle n_{q+g} \rangle = 2n_f + \mathcal{O}(\frac{1}{\alpha_s}) \gtrsim 10$
- (approximate) Poisson distribution of gluon multiplicity

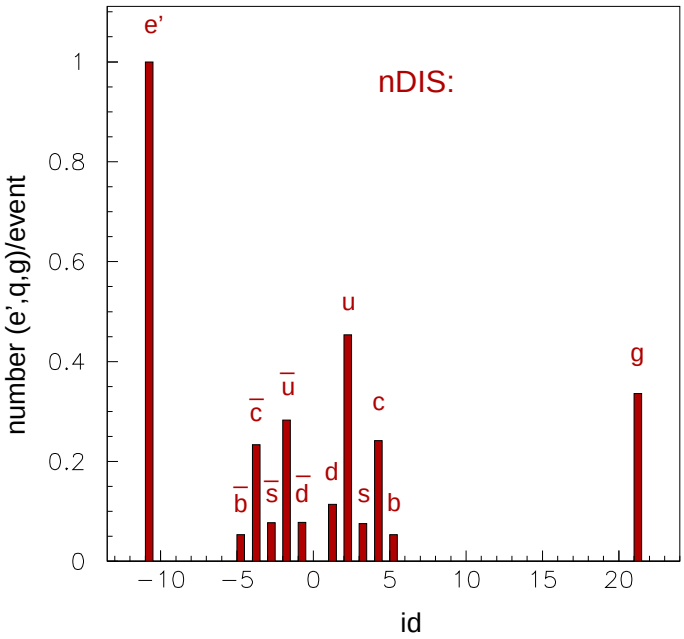
♢ Leading-log parton shower & hadronization
(default: **HERWIG 5.9**, optional: **JETSET**)

- parton content/event from QCDINS and normal DIS (nDIS)





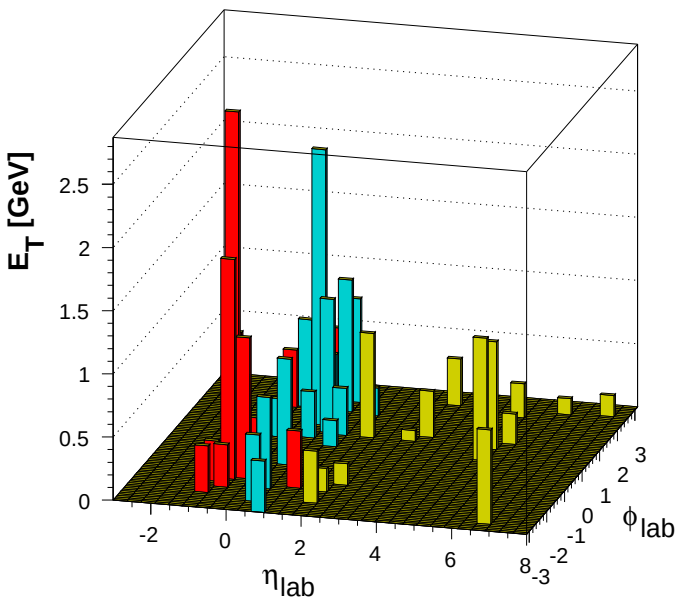




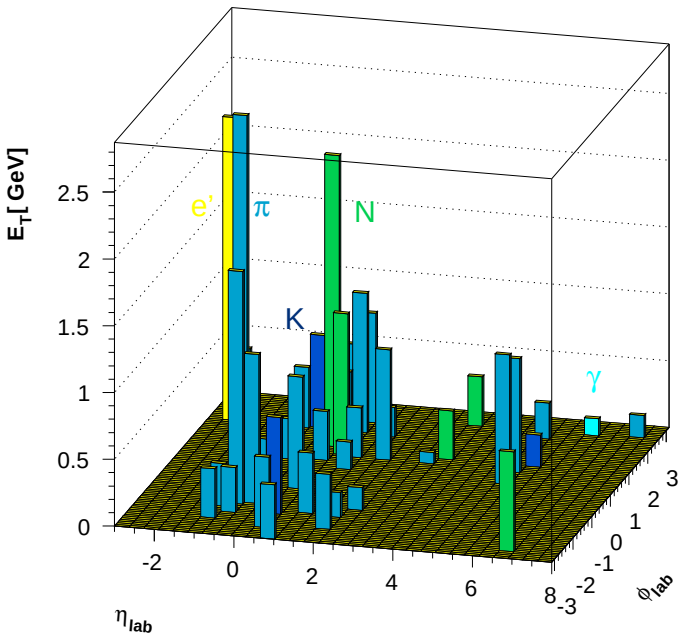
- **INS:** flavour of current $q/\overline{q}$ couples $\propto e_q^2$ i.e. $u : d = 4 : 1$.
- **INS partonic final state:** flavour democracy!, i.e. $(n_f\, q \oplus n_f\, \overline{q} \oplus \mathcal{O}(\frac{1}{\alpha})\, g)$/event i.e. $\mathcal{O}(10)$ partons/event!

Characteristic Final-State Signature

Characteristics



Particle Composition



- current jet

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

  ◊ large total E_t

  ◊ large multiplicity

  ◊ (light) flavour "democracy" : $\star$ **strangeness** $\Rightarrow \left\{ \begin{array}{l} K's \\ \Lambda's \end{array} \right.$

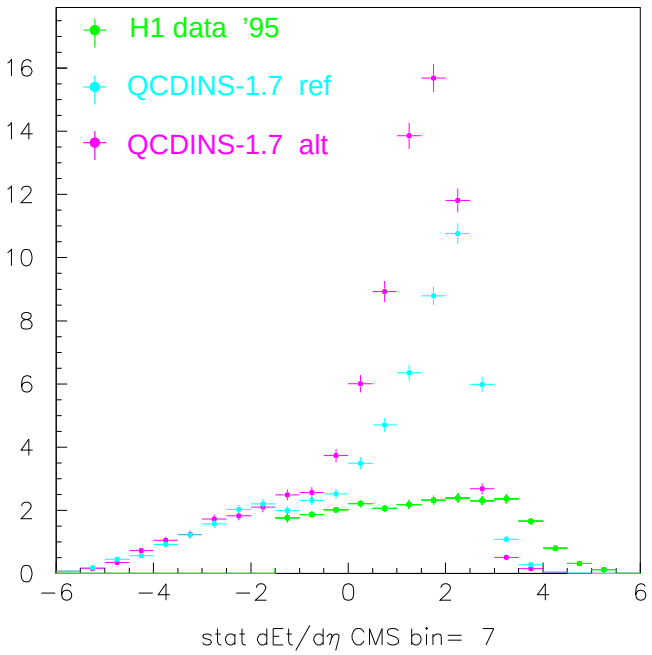
  ◊ no further jets

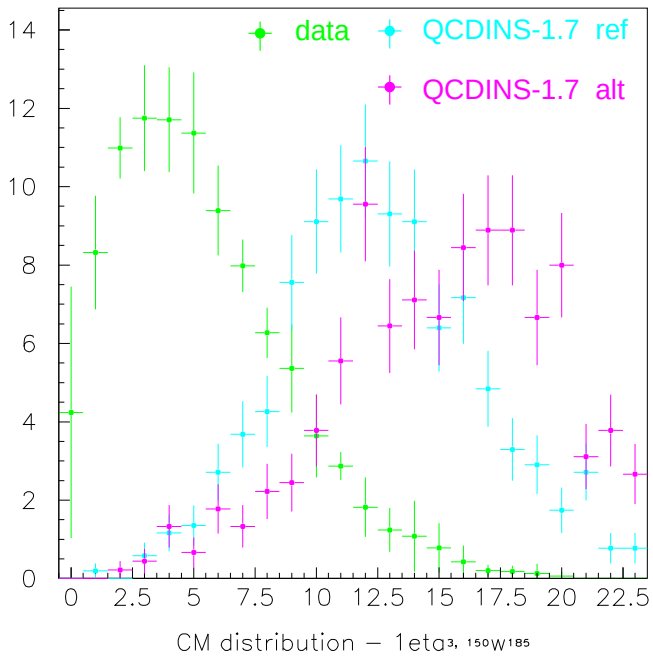
- **INS**-predictions for characteristic observables and published **HERA** data (green)[⇐ HZTOOLS package], hadronic CMS

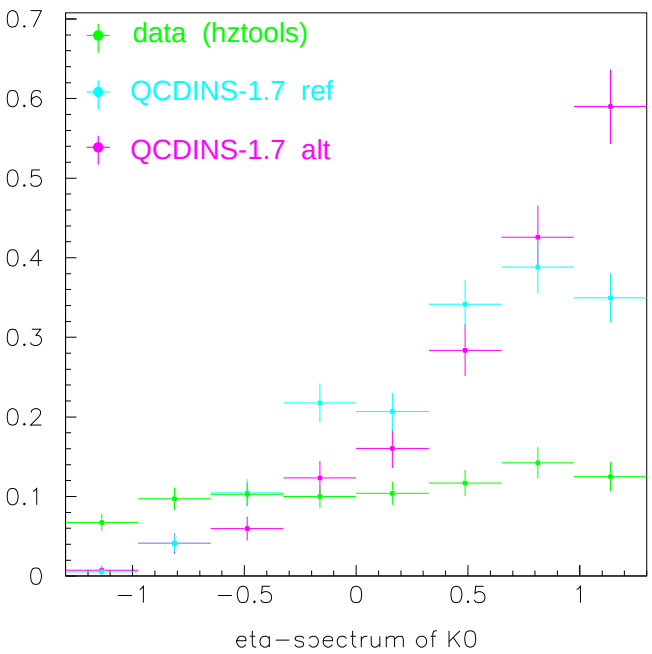
$$\text{“ref”} = (\rho \lesssim 0.36\ \text{fm}, R/\rho \gtrsim 1.07) \quad \Leftrightarrow \quad (Q' \gtrsim 10.4\ \text{GeV}, x' \gtrsim 0.35)$$

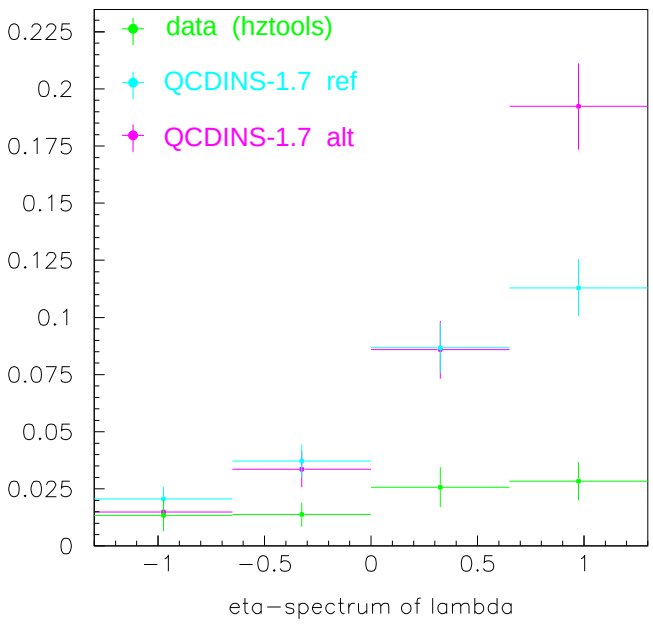
$$\text{“alt”} = (\rho \lesssim 0.30\ \text{fm}, R/\rho \gtrsim 0.92) \quad \Leftrightarrow \quad (Q' \gtrsim 14.1\ \text{GeV}, x' \gtrsim 0.26)$$

$$\sigma^{(I)}{}_{\text{HERA}}(\text{“ref”}) \simeq \sigma^{(I)}{}_{\text{HERA}}(\text{“alt”})!$$









Search Strategies and Model Dependencies

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

♣ Goals and Questions:

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

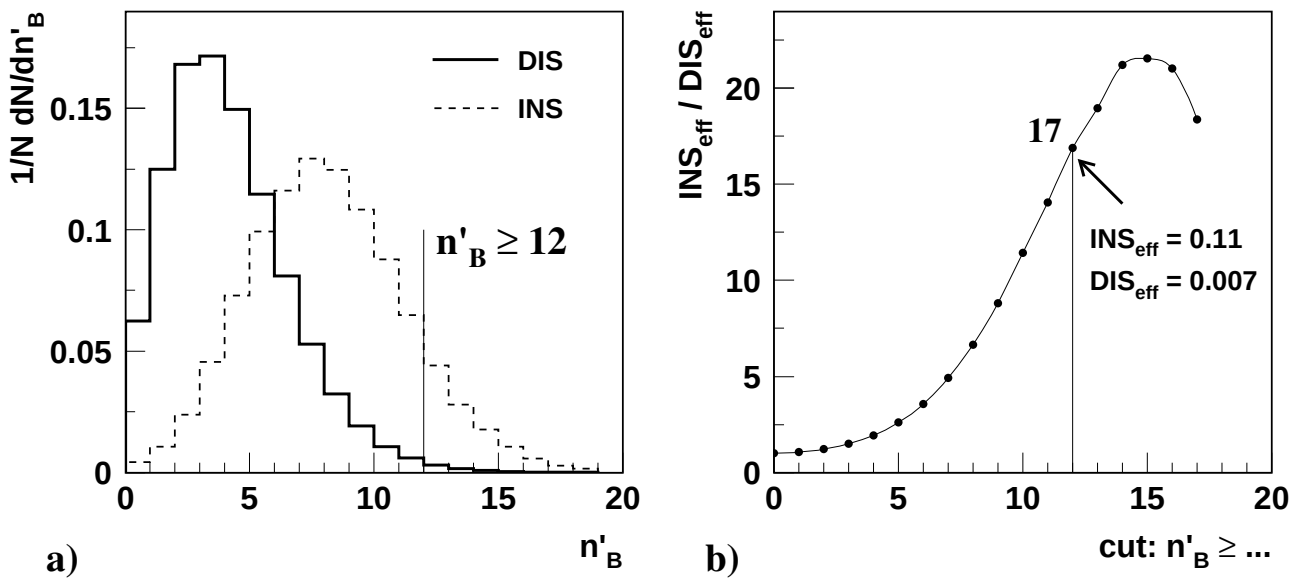
⇒ B) Dependencies on MC models, both for INS and DIS events

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

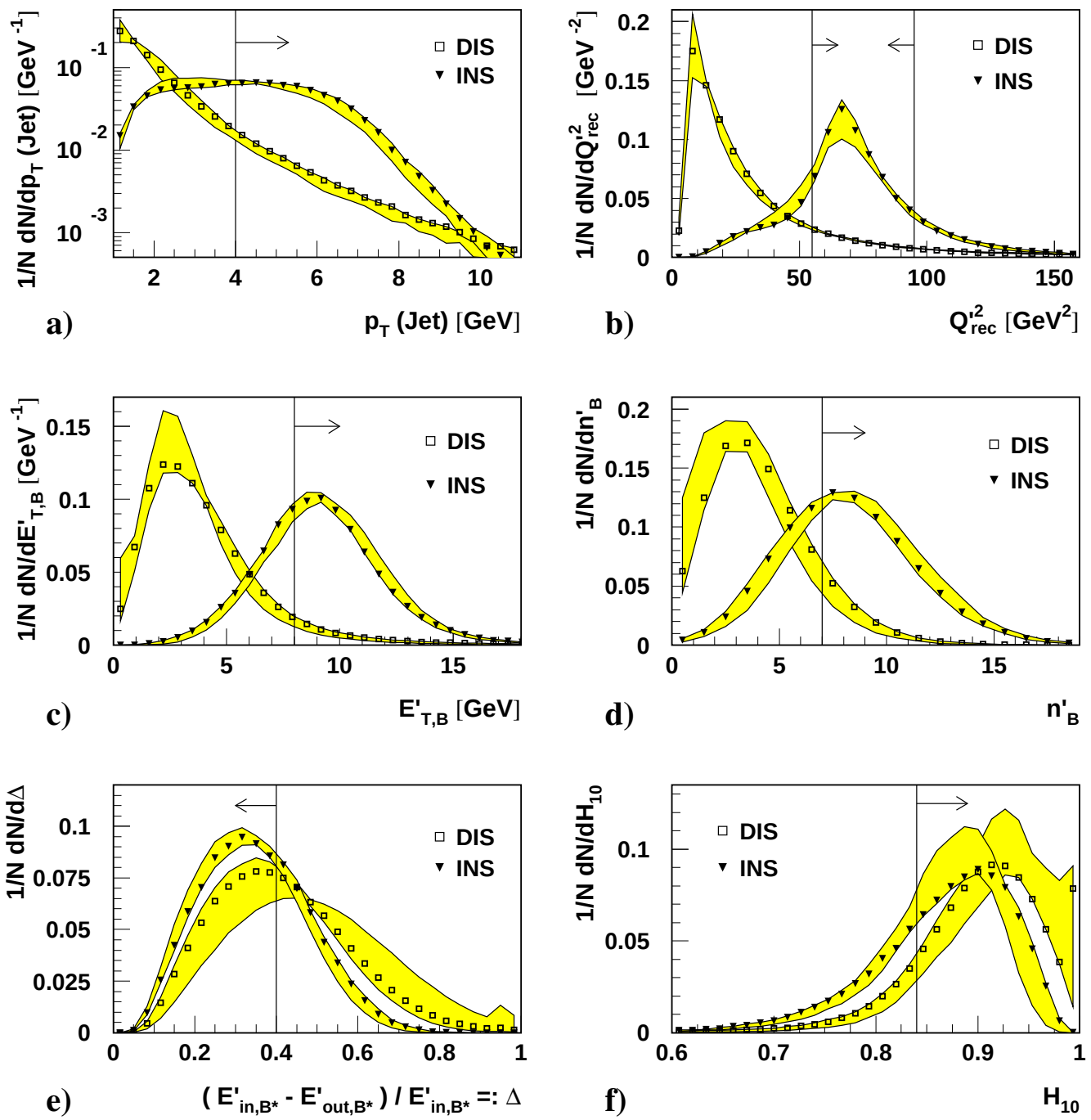
(A) I-enriched data sample: ($INS_{\rm eff} \gtrsim 10\%$)

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

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



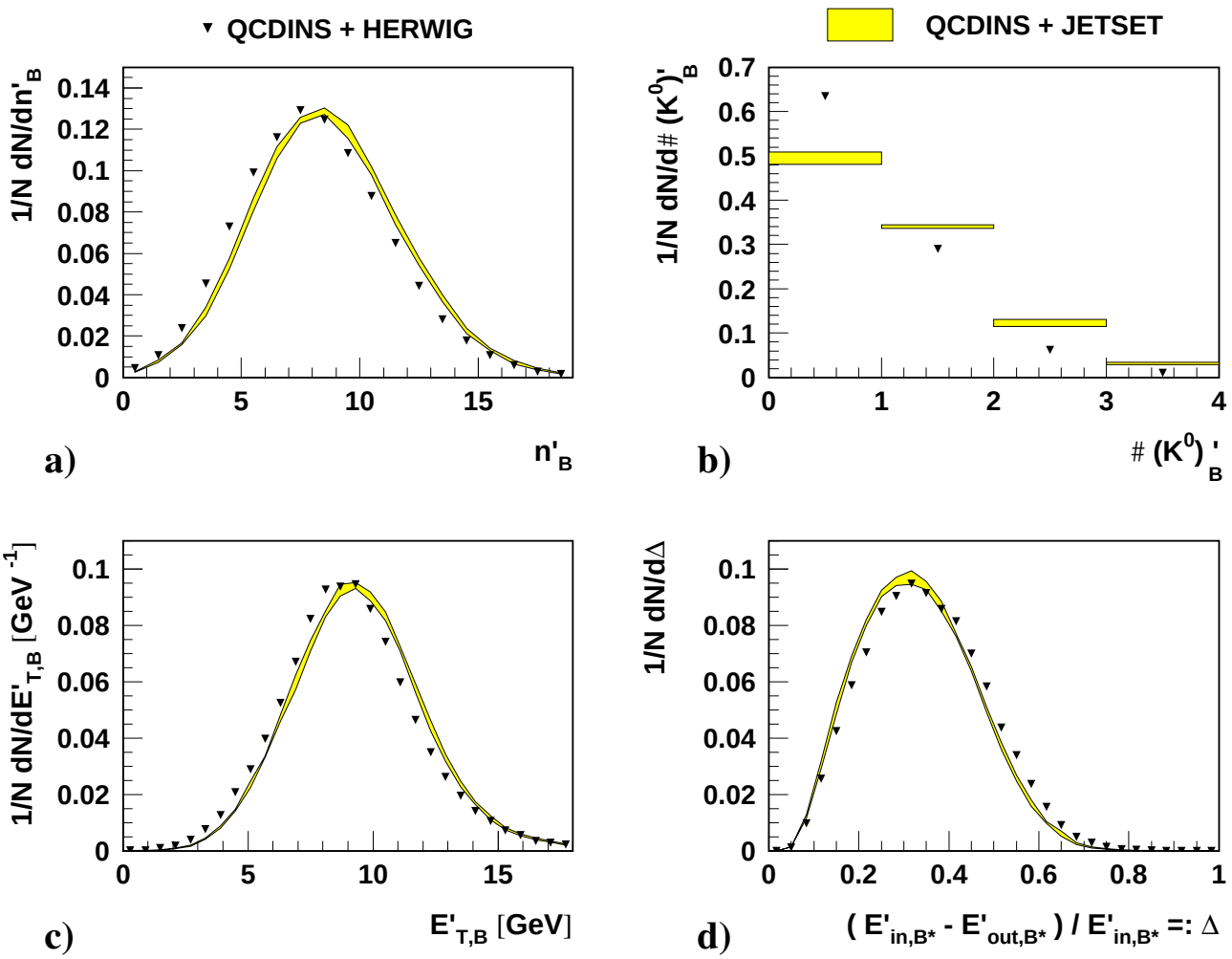
- Set of 6 "best" observables (among ~ 30) enhance I-separation power to $\mathcal{O}(130)$:



(B) MC model dependencies:

- **QCDINS**: HERWIG (default)⇒ JETSET[1]

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



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

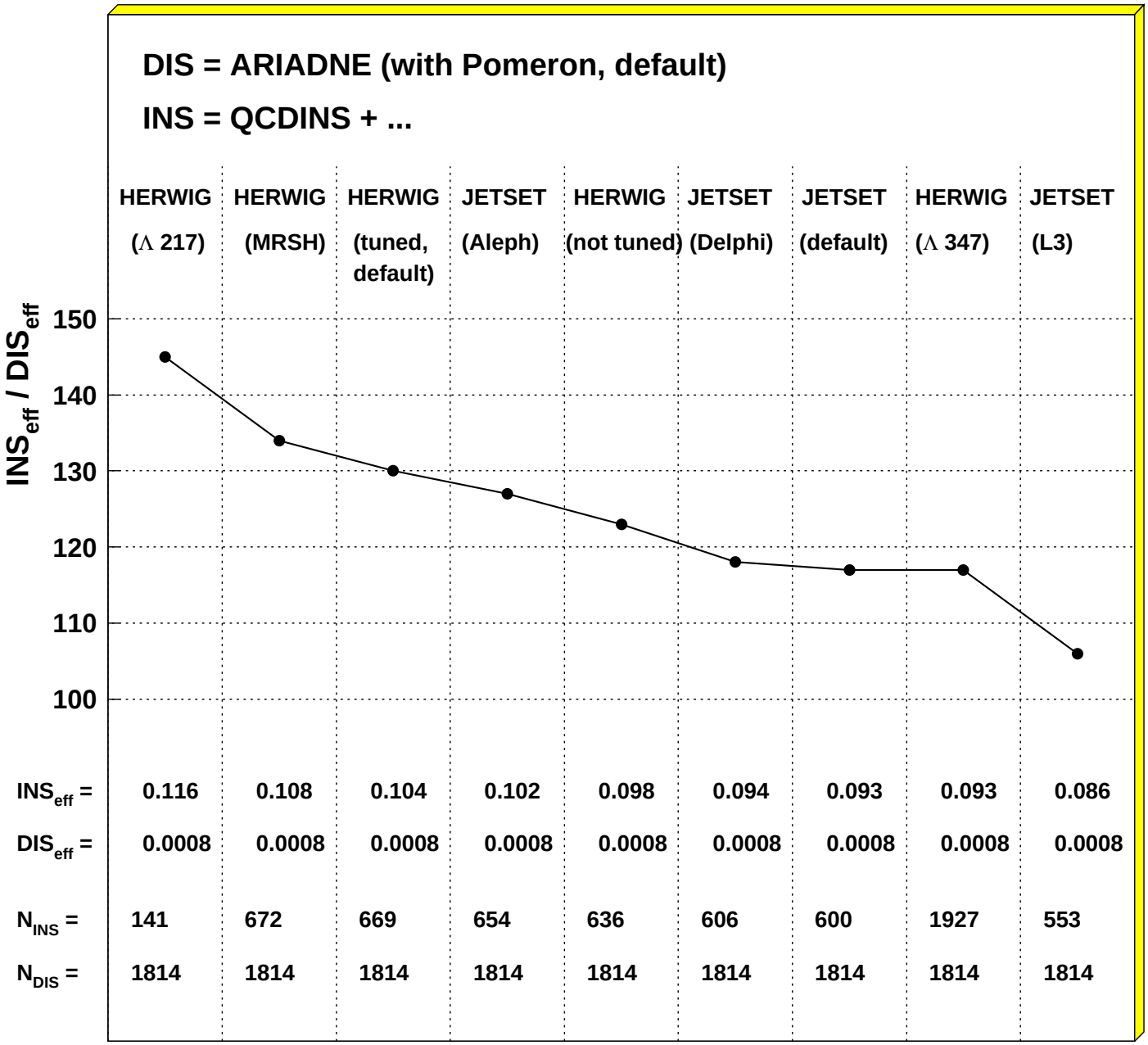
[1] thanks to Hannes Jung!

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

Cuts:

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

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



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

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

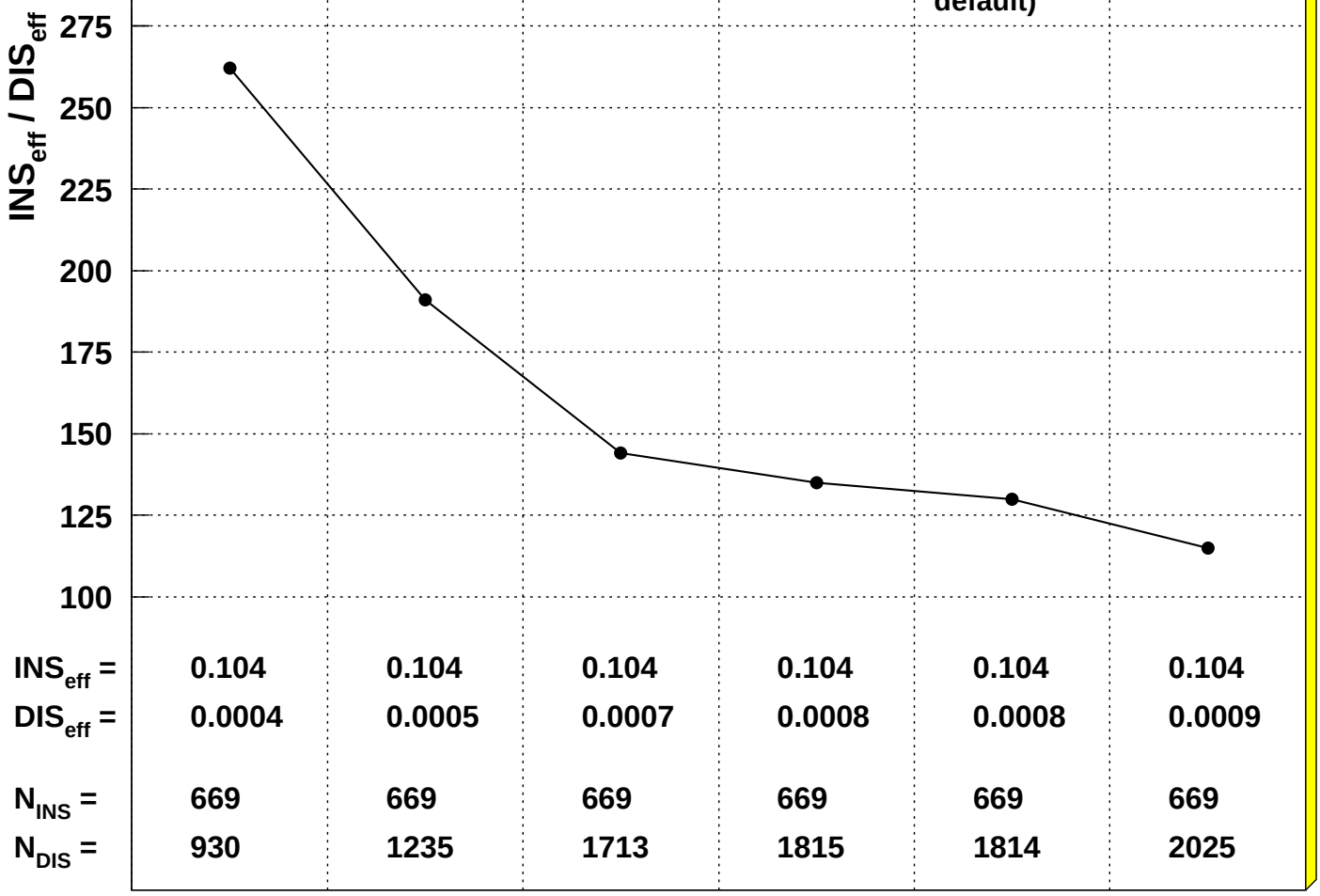
Cuts:

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

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

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 I-separation power (≈ 130)

♢ **INS**: Within "bandwidth" studied, surprisingly small systematics from varying the modelling of I-induced events

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

I-Discriminants, a Better Way? (in progress)

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

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

  I-discriminating variable, that peaks if there is an I-signal

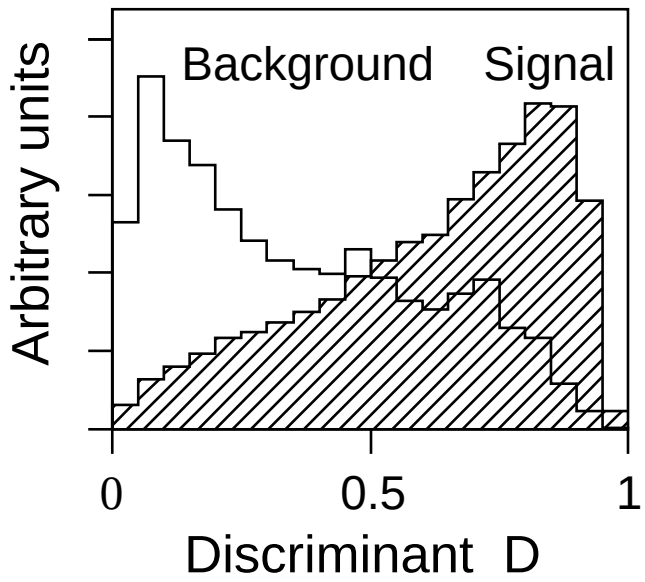
- Increase sensitivity, by treating observables $\vec{O}$ collectively rather than cutting on each separately!
- Conceptually related to neural-network filters, that also look promising. . . [MPI, Munich]
- Let $s_i(O_i)$ and $b_i(O_i)$ be norm. distributions of O_i for signal and background, respectively

$$D \equiv \frac{f_s(\vec{O})}{f_s(\vec{O}) + f_b(\vec{O})}$$

$$f_s(\vec{O}) \equiv \prod_{i=1}^{n} s_i^{w_i}(O_i)$$

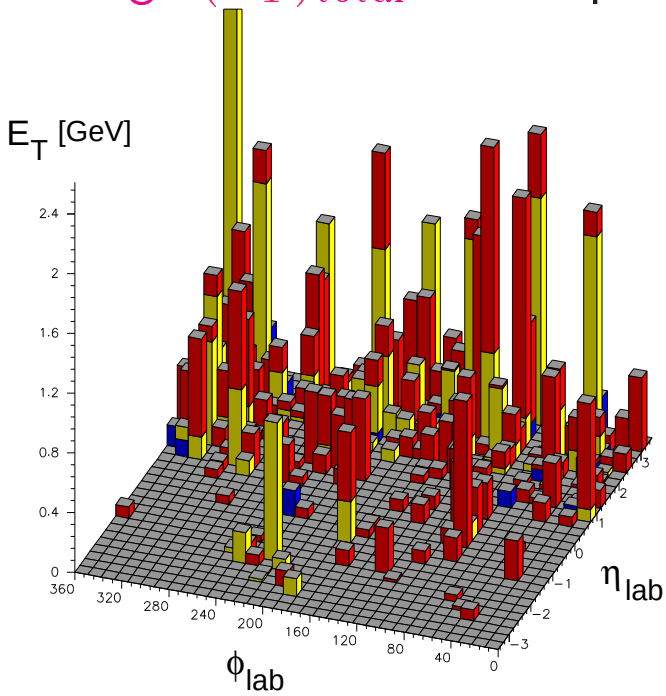
$$f_b(\vec{O}) \equiv \prod_{i=1}^{n} b_i^{w_i}(O_i)$$

likelihood function if no corr.'s

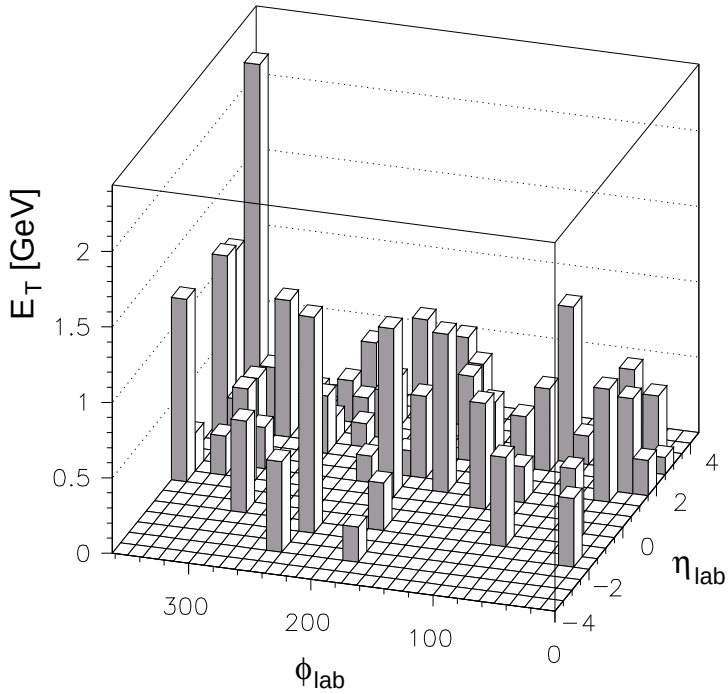


I-Induced Processes at small Q^2 (Photoproduction)?

- At small Q^2, a number of spectacular "fireball" events with large $(E_T)_{\text{total}}$ were reported [Y. Yamazaki (ZEUS), Durham '98]



ZEUS-home page, DESY



QCDINS

♣ Seem to exhibit all characteristics of I-induced processes

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

- Fireball events in photoproduction look "inspiring" . . .

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