Instantons

in the QCD Vacuum and in DIS

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in collaboration with

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1. **Introduction**
2. **Instantons in the QCD Vacuum** $\Leftarrow$ **Lattice**
3. **Search Strategies and**
   Model Dependencies in DIS

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– DIS 99, Zeuthen, April 1999 –

1. Introduction

- Ground-state ("vacuum") of non-abelian gauge theories like QCD : Very rich

♣ Including topologically non-trivial fluctuations of the gauge fields, carrying an integer topological charge Q

- Simplest building blocks of topological structure, localized ("instantaneous") in time and space: [Belavin *et al* '75, 't Hooft '76]

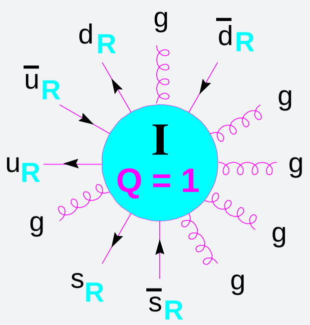
Instantons $(Q = +1)$ and **anti-instantons** $(Q = -1)$

◇ Explicit solutions of classical (Euclidean) field equations
◇ Tunnelling transitions between adjacent, topologically inequivalent vacua

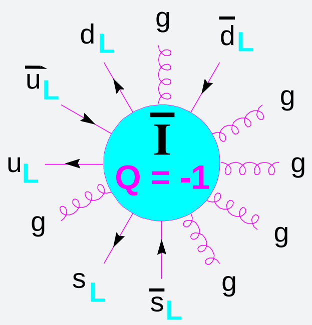
- Play important rôle in various long-distance aspects of QCD

♣ Also important short-distance implications:

Induce processes violating "chirality" $= \#(q_{\rm R}) - \#(q_{\rm L})$ in (massless) QCD :



$$\Delta\, Q_5 = 2 n_{\rm f} \cdot Q$$



– in accord with general Adler-Bell-Jackiw ANOMALY

– forbidden in ordinary perturbation theory $(Q = 0\,!)$

- An experimental discovery of instanton-induced processes, as a novel, non-perturbative manifestation of QCD would be of basic significance $\Leftarrow$ **HERA !**

- **DIS** distinguished, since hard instanton-induced processes

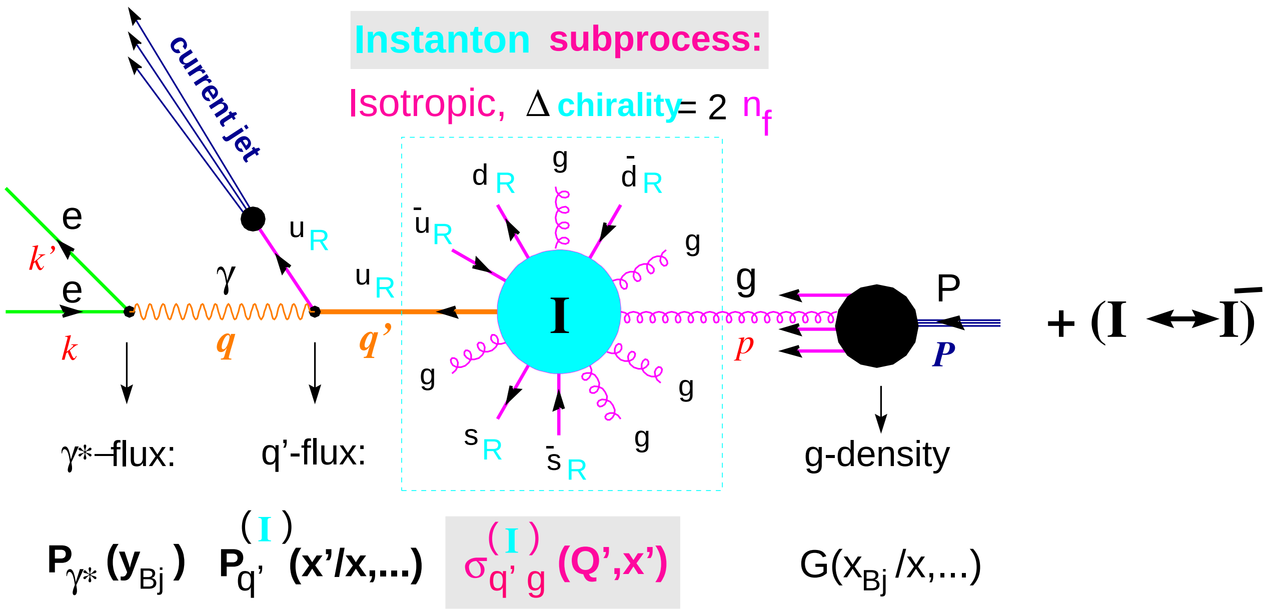
  ♣ are calculable within instanton-perturbation theory

  [Balitsky & Braun '93; Ringwald & F. Sch. '94 - '98; Moch, Ringwald & F. Sch. '97]

  ♣ can possibly also be detected experimentally $\Leftarrow$ **HERA** .

  [Ringwald & F. Sch. '94 - '98]

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



2. Instantons in the QCD Vacuum $\Leftarrow$ Lattice

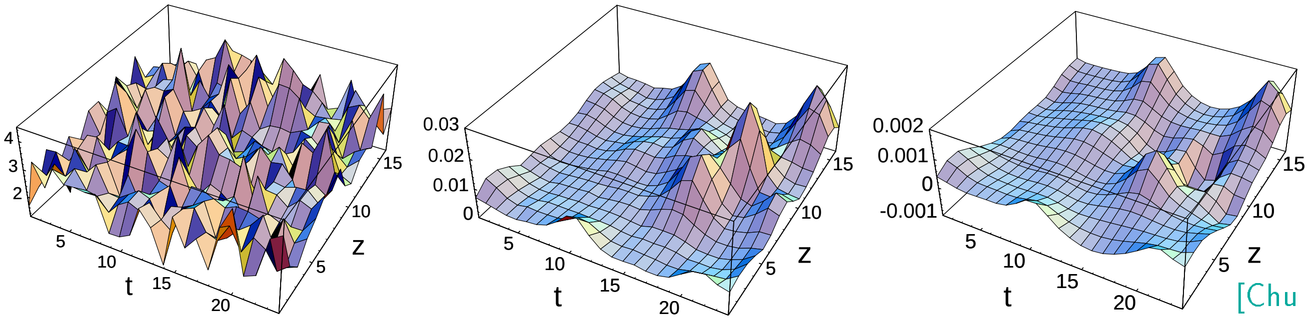
[Ringwald & F. Sch., hep-ph/9812359, Phys. Lett. **B 438** (1998) 217, hep-lat/9903039]

- Crucial information on range of validity of our **DIS** predictions from recent high-quality **lattice** simulations of $\mathrm{QCD}_{\,\mathrm{n_f=0}}$

- $\Rightarrow$ "Snapshots" of QCD -vacuum in space-time, including all non-perturbative, topological features like instantons!

- Cooling: Designed to filter out (dominating) fluctuations of short wavelength $\mathcal{O}(a)$, while affecting topological fluctuations of size $\rho \gg a$ comparatively little.

Lagrange Density **Topological Charge Density**



[Chu *et. al* '94]

- E. g. here, see 3 instantons (I) and 2 anti-instantons ($\bar{I}$)

♣ Link I-observables in **DIS** and in the QCD vacuum (lattice):

- **DIS:** I-rate at HERA in terms of I-subprocess cross-section, based on I-perturbation theory for dilute I gas

$(Q'^2 \equiv -q'^2$ large, $x' = \frac{Q'^2}{2p\cdot q'}$ fixed, $p^2 = 0)$:

$$\boxed{\begin{aligned}\sigma^{(\boldsymbol{I})}(q'\,p \Rightarrow X) = \int d^4R\; e^{i\,(p+q')\cdot R} \int_0^\infty d\rho \int_0^\infty d\overline{\rho}\; F(Q'\,\rho)\,F(Q'\,\overline{\rho}) \\ \times\; D(\rho)\,D(\overline{\rho}) \int dU\; e^{-\frac{4\pi}{\alpha}\,\Omega\left(U,\frac{R^2}{\rho\overline{\rho}},\frac{\overline{\rho}}{\rho}\right)}\;\{\ldots\}\end{aligned}}$$

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

◇ $\boxed{\textbf{known}}$ in $\boldsymbol{I}$-pert. theory, for $\alpha(\mu_r)\ln(\mu_r\rho) \ll 1$ and $R^2/\rho\overline{\rho} \gg 1$, respectively ($\mu_r$ = renorm. scale).

◇ $\Omega\left(U, \frac{R^2}{\rho\overline{\rho}}, \frac{\overline{\rho}}{\rho}\right)$ analytically known within "$I\overline{I}$-valley" approximation [Yung '88, V.V. Khoze & Ringwald '91, Verbaarschot '91]

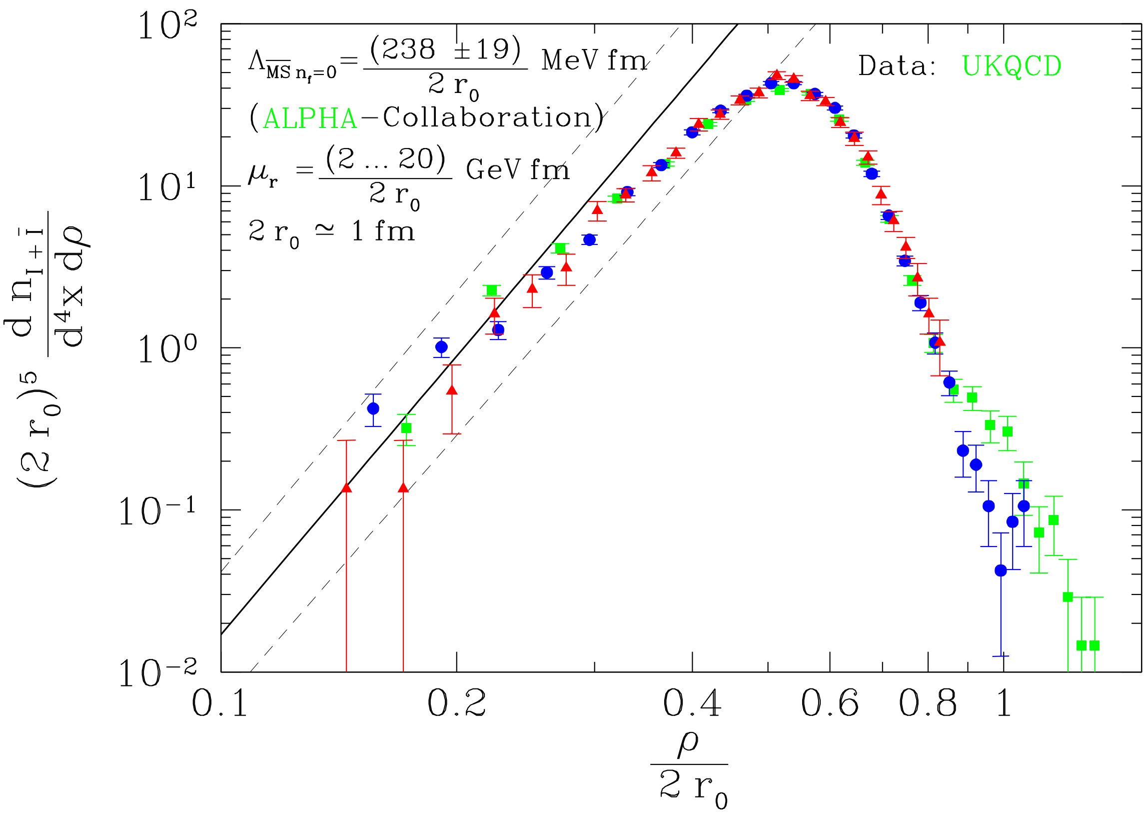
◇ Powerlaw behaviour $D(\rho) \propto \rho^{6-2/3n_f+\mathcal{O}(\alpha)}$ generically spoils applicability of $\boldsymbol{I}$-perturbation theory, since $\boldsymbol{I}$-size integrals diverge, except in **DIS**, where "form factors" $F(Q'\,\rho)\,F(Q'\,\overline{\rho}) \propto \exp(-Q'(\rho + \overline{\rho}))$ insure $\rho \lesssim 1/Q'$

- QCD Vacuum (lattice): $\Leftarrow$ high-quality lattice data: [UKQCD, Smith & Teper '98]

- Measured: $\frac{d(n_{I+\bar{I}})}{d^4x\, d\rho}$ = Number of I's and $\bar{I}$'s per unit volume per unit size (pattern recognition)

- Perform continuum limit, account for cooling effects, conversion to physical units: "Sommer scale" $2r_0 \simeq 1$ fm . . .

[Ringwald, F. Sch., hep-ph/9812359, hep-lat/9903039]



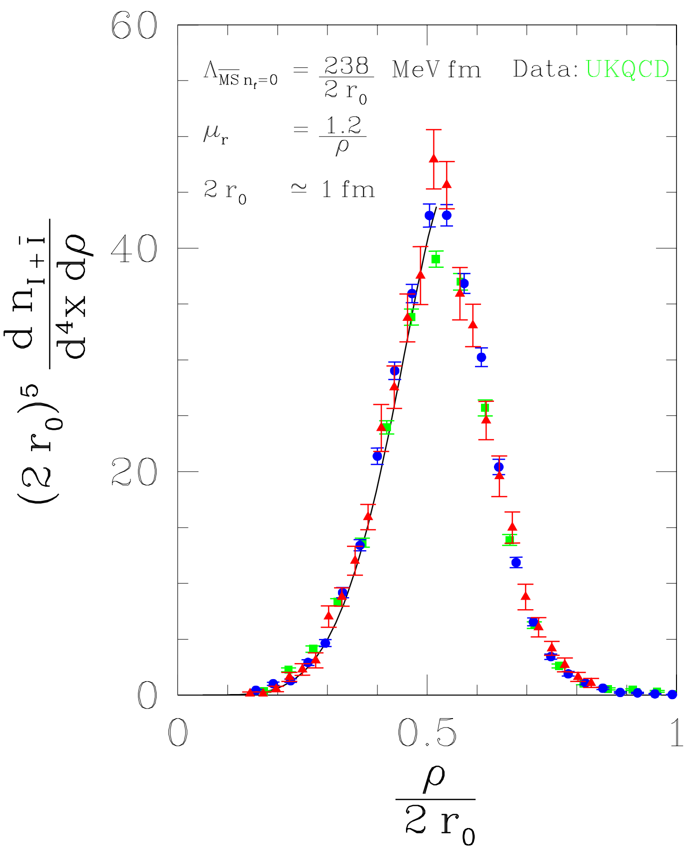
- Parameter-free **agreement** in shape and normalization,

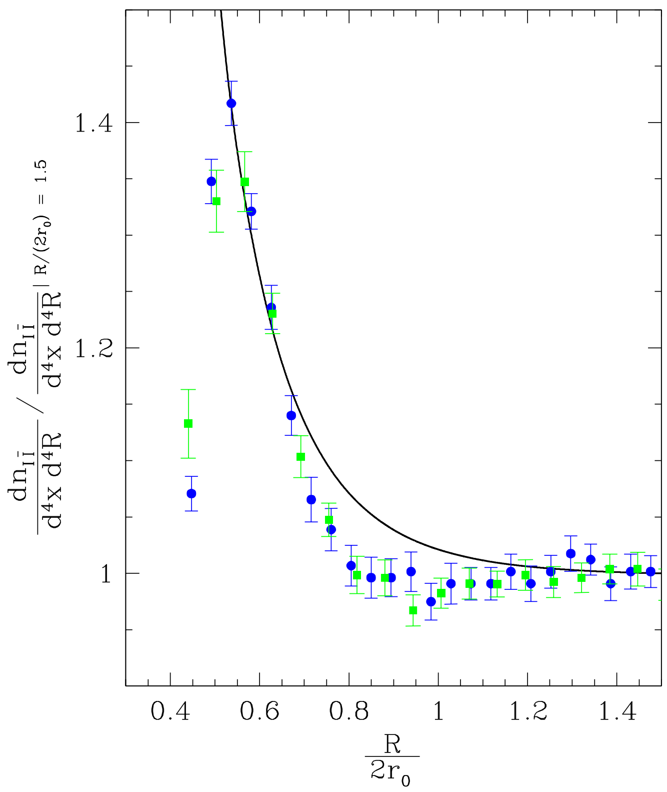
$$(2r_0)^5 \frac{d(n_{I+\bar{I}})}{d^4x\, d\rho} \simeq 2\, D(\rho)_{|I-\text{ pert. theory}},$$ for $\rho \lesssim 0.3$ fm

- Error band $\Leftrightarrow$ error of $2r_0\Lambda_{\overline{\mathrm{MS}}\, n_f=0} = (238 \pm 19)$ MeV fm

[ALPHA-Collaboration, hep-lat/9810063]

- Almost independent of μ_r for large range $2 \lesssim \mu_r \lesssim 20$ GeV.
- 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 !





- Measured: $\frac{d(n_{I\bar{I}})}{d^4x\, d^4R}$ = Distance distribution of $I\bar{I}$-pairs
- First direct test of $I\bar{I}$-valley form for $I\bar{I}$-interaction Ω!

$$\frac{d(n_{I\bar{I}})}{d^4x\, d^4R} \stackrel{?}{\simeq} N \int_0^\infty d\rho \int_0^\infty d\bar{\rho}\; D(\rho)\, D(\bar{\rho}) \int dU\, \mathrm{e}^{-\frac{4\pi}{\alpha}\, \Omega\left(U, \frac{R^2}{\rho\bar{\rho}}, \frac{\bar{\rho}}{\rho}\right)}$$

- Substitute $D(\rho)$ by fit of lattice data, $\alpha = \alpha_{\overline{\rm MS}}(\frac{\mathcal{O}(1)}{\sqrt{\rho\bar{\rho}}})$
- Good **agreement** for $R \gtrsim 0.5$ fm, i. e. $R/\rho \gtrsim 1$

♣ In summary:

◇ Good **agreement** of lattice results with $\boldsymbol{I}$-perturbation theory very interesting by itself.

◇ Lattice constraints translate into "fiducial" kinem. region in **DIS**:
$$\left.\begin{array}{lll} \rho & \lesssim & 0.3\ \mathrm{fm} \\ R/\rho & \gtrsim & 1 \end{array}\right\} \Rightarrow \left\{\begin{array}{lll} Q' & \gtrsim & 8\ \mathrm{GeV} \\ x' & \gtrsim & 0.35. \end{array}\right.$$

◇ 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, high-E_T fireballs in photoproduction. . .

3. Search Strategies and Model Dependencies in DIS

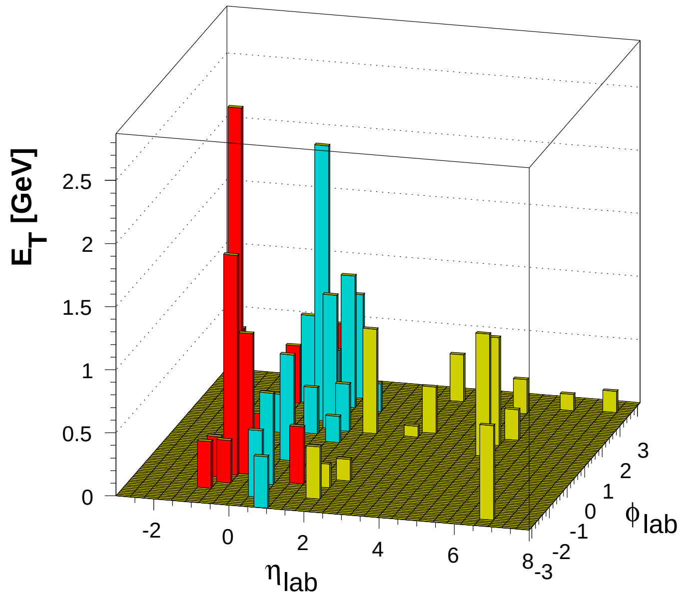
[T. Carli, J. Gerigk, A. Ringwald, F. Sch., '99]

♣ Theoretical state of the art: [Ringwald, F. Sch., Phys. Lett. **B438** ('98)]

- **HERA**: High rate of $\boldsymbol{I}$-events in "fiducial" **DIS** region with substantial uncertainties:

$$\Lambda_{\overline{\mathrm{MS}}\, n_f=3} = (282 \pm 65)\ \mathrm{MeV} \;\Rightarrow \sigma^{(I)}{}_{\mathrm{fiducial}} \simeq \mathbf{126}^{+300}_{-100}\ \mathrm{pb}.$$

- Characteristic signature:



– Current jet

– I-"band" ($\Leftarrow$ Isotropy)

◇ Large E_T,

◇ Large multiplicity,

◇ Flavor "democracy":

⋆ **Strangeness** $\Rightarrow$ K_S^0's

- Important tool: "QCDINS 1.6.0" [Gibbs, Ringwald & F. Sch. '95]
  Monte-Carlo generator for I-induced DIS-events

  ◇ Instanton-induced hard subprocess

  ◇ Leading-log parton shower & hadronization (HERWIG 5.9)

♣ Questions and Goals: [T. Carli, J. Gerigk, A. Ringwald, F. Sch., '99]

A) Bjorken variables (Q', x') of I-subprocess?

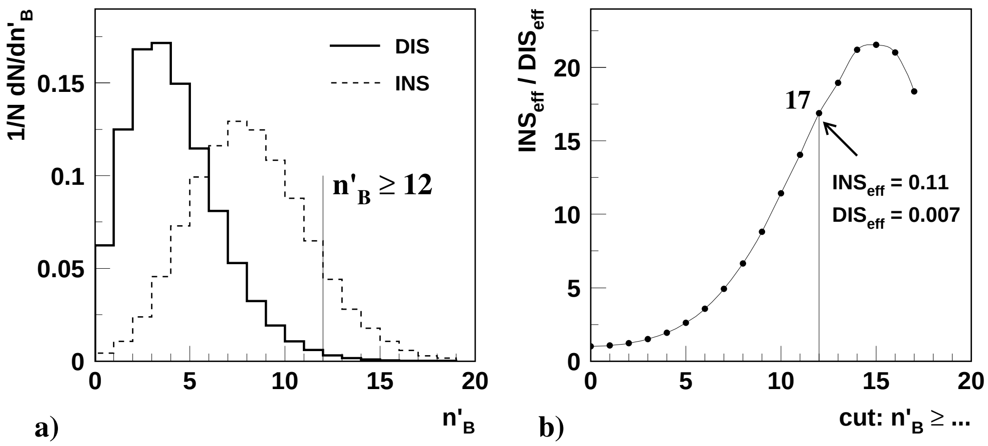
$\Rightarrow$ B) Isolate I-enriched data sample by means of cuts to a set of observables. Optimize separation power:$=\frac{INS_{\rm eff}}{DIS_{\rm eff}}$.

$\Rightarrow$ C) Dependencies on MC models, both for INS and DIS events

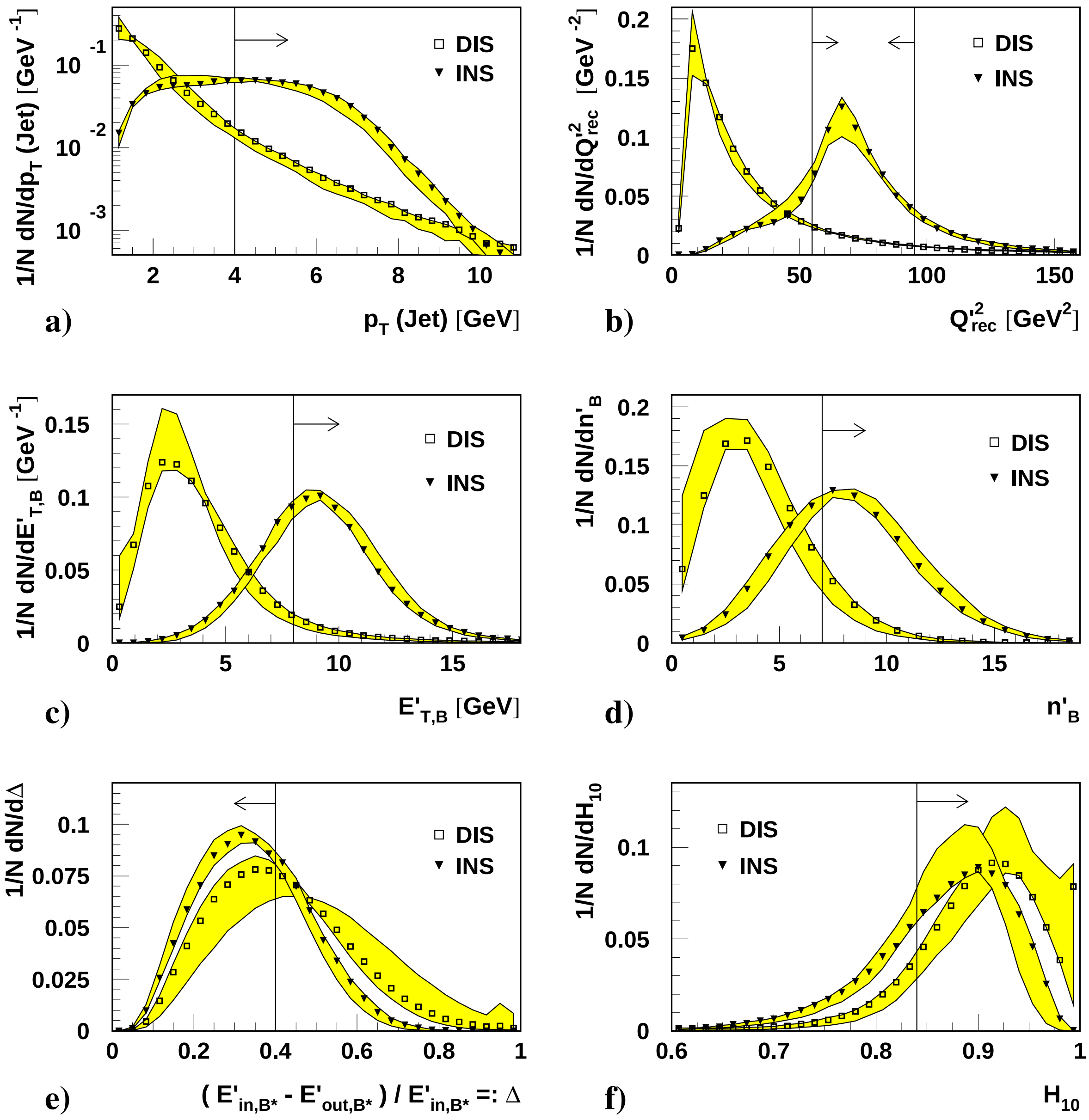
(B) I-enriched data sample: ($INS_{\rm eff} \gtrsim 10\%$)

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

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



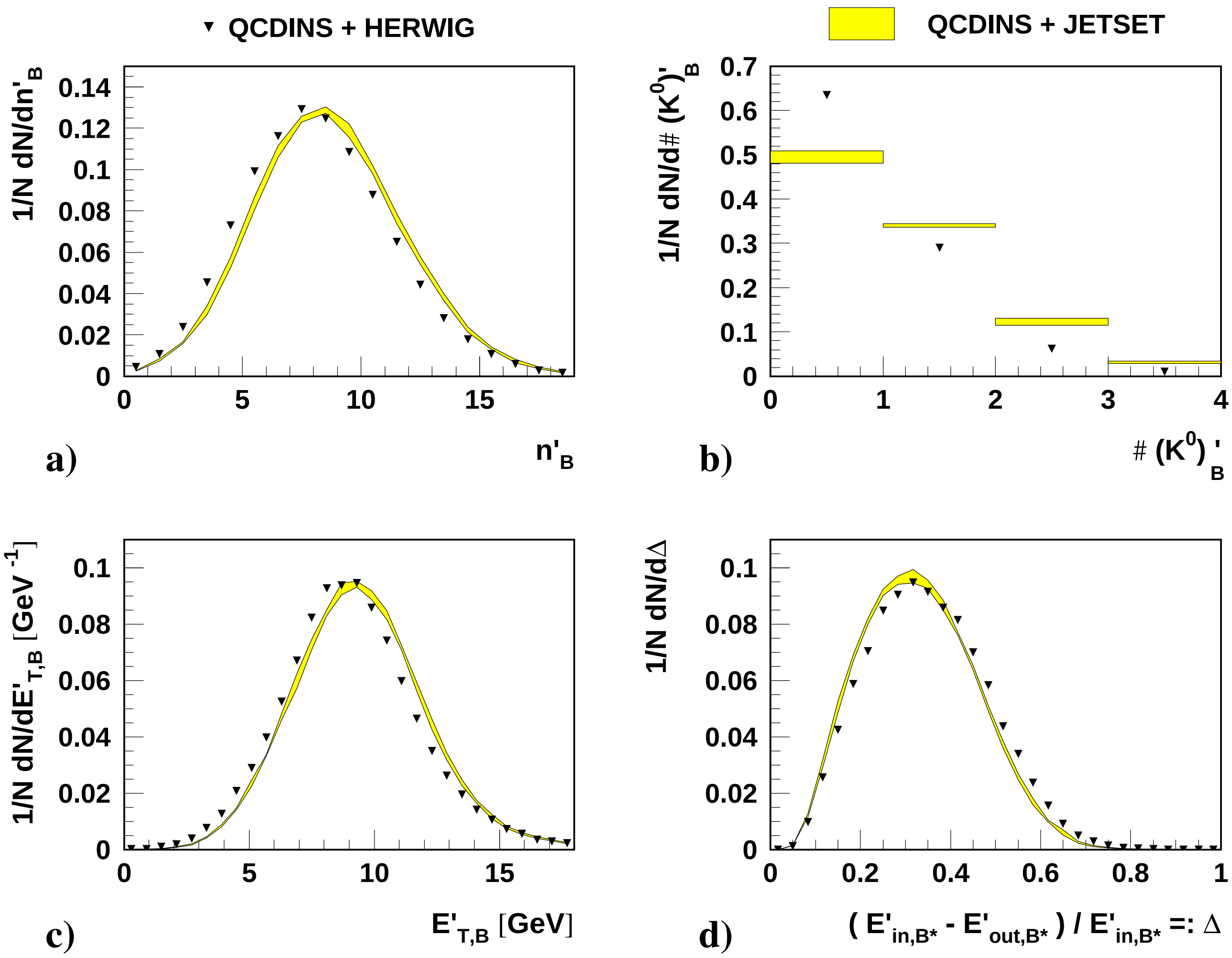
- Set of 6 "best" observables (among ~ 30) enhance separation power to $\boxed{\mathcal{O}(130)}$:



(C) MC model dependencies:

- **QCDINS**: HERWIG (default) $\Rightarrow$ JETSET[1]

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



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

[1] thanks to Hannes Jung!

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

Cuts:

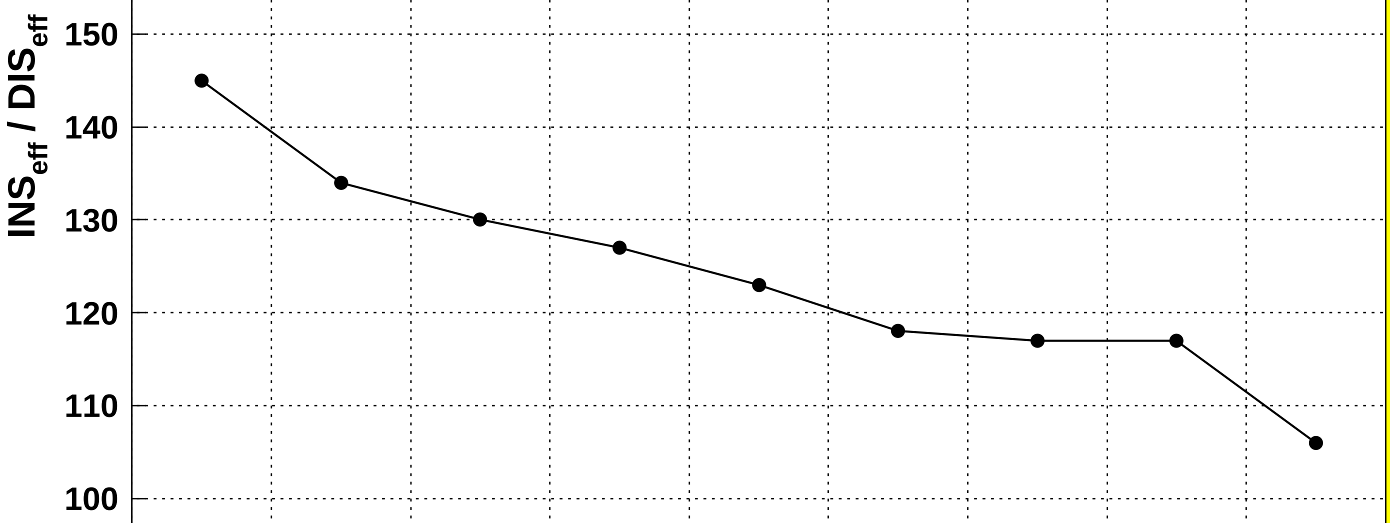
$55\ \mathrm{GeV}^2 < Q'^2_{rec} < 95\ \mathrm{GeV}^2$ $p_T\,(\mathrm{Jet}) > 4$ GeV $E'_{T,B} > 8$ GeV

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

DIS = ARIADNE (with Pomeron, default)

INS = QCDINS + ...

	HERWIG (Λ 217)	HERWIG (MRSH)	HERWIG (tuned, default)	JETSET (Aleph)	HERWIG (not tuned)	JETSET (Delphi)	JETSET (default)	HERWIG (Λ 347)	JETSET (L3)



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

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

Cuts:

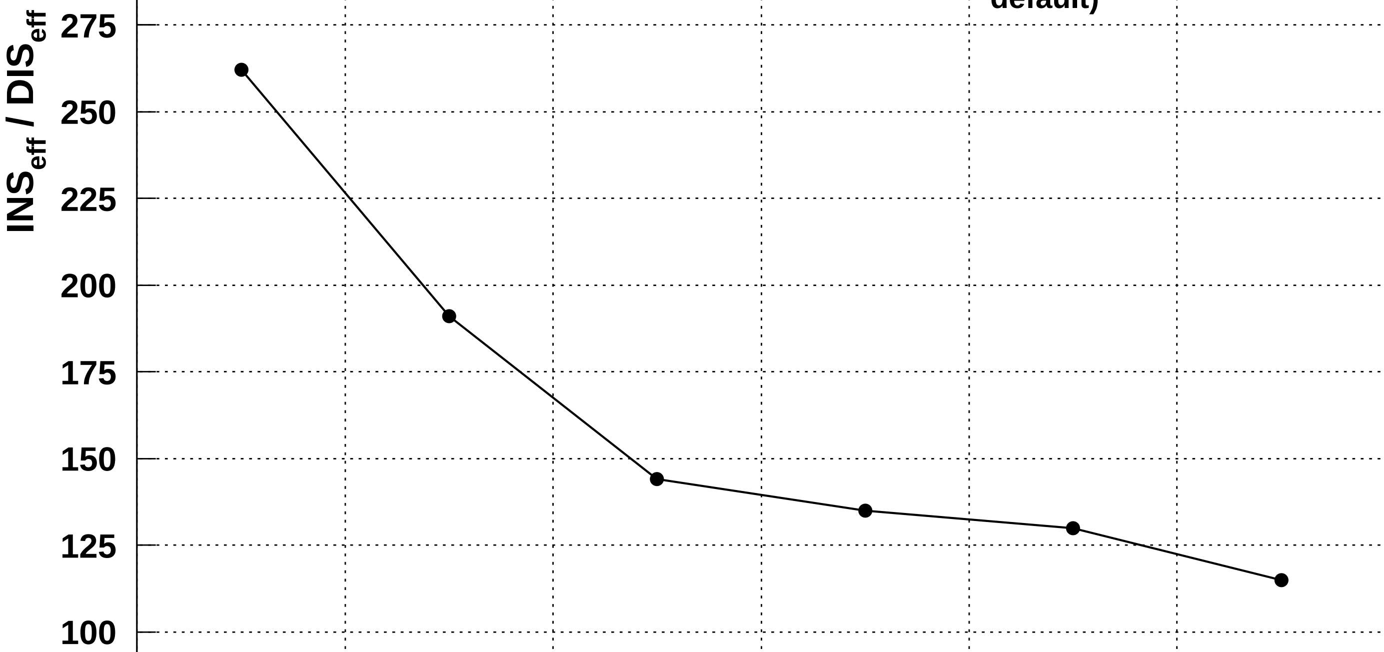
$55\ \text{GeV}^2 < Q'^2_{rec} < 95\ \text{GeV}^2$ $\quad p_T\ (\text{Jet}) > 4$ GeV $\quad E'_{T,B} > 8$ GeV

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

INS = QCDINS + HERWIG tuned (default)

DIS = ...

	HERWIG (tuned)	HERWIG (not tuned)	LEPTO (SCI)	LEPTO (no SCI)	ARIADNE (Pomeron, default)	ARIADNE (no Pom.)



	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:

- Found set of (6) observables with good I-separation power
- **INS**: 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 most important!