# Search for QCD Instanton-induced Processes in DIS at HERA

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for the H1 Collaboration

- Instantons in QCD and DIS
- Search Strategy
- Results
- Summary

ICHEP2000, Osaka July 27–August 2, 2000

# Further reading

Instanton-Perturbation Theory in DIS

A. Ringwald and F. Schrempp,
Nucl. Phys. B 507 (1997) 134
A. Ringwald and F. Schrempp,
Phys. Lett. B 438 (1998) 217
A. Ringwald and F. Schrempp,
Phys. Lett. B 459 (1999) 249
Update: papers 250, 251, 252, 254, 255 ICHEP2000
...and more !

Experimental searches and strategies

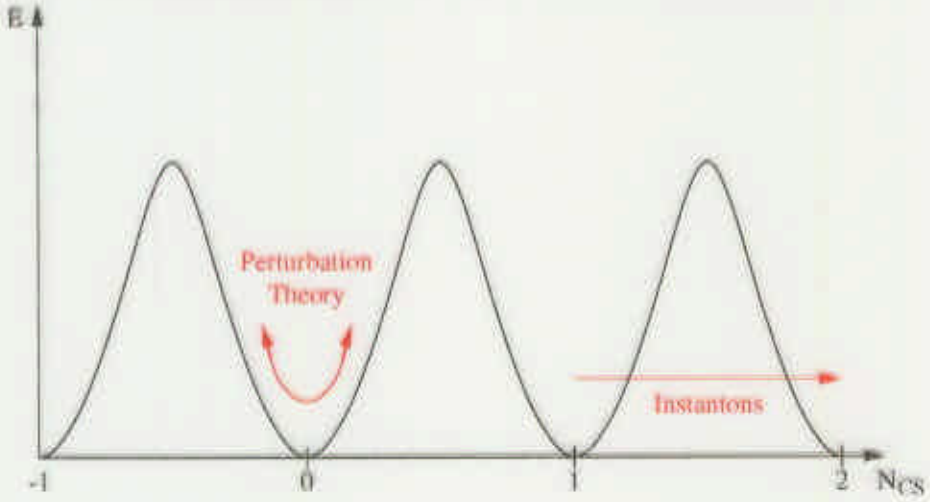
T. Carli and M. Kuhlen,
Nucl.Phys. B511 (1998) 85
T. Carli, J. Gerigk, A. Ringwald and F. Schrempp,
hep-ph/9906441

See also A. Ringwald and F. Schrempp

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

Many thanks to T. Carli
S. Hikocki
F. Schrempp for help.

# What are Instantons?




- Tunneling transitions between topologically inequivalent ground-states (feature of non-abelian theories)
- exponentially suppressed $\sim e^{-4\pi/\alpha_s}$ $\Delta\alpha_s$ has huge effect!
- may become observable at high energies via production of additional gauge bosons (Ringwald, Espinosa 90)
- processes which violate quantum number conservation. In QCD: Chirality: $\#(q_R) - \#(q_L)$ is normally conserved
- not present in conventional perturbation theory
- but... part of standard model

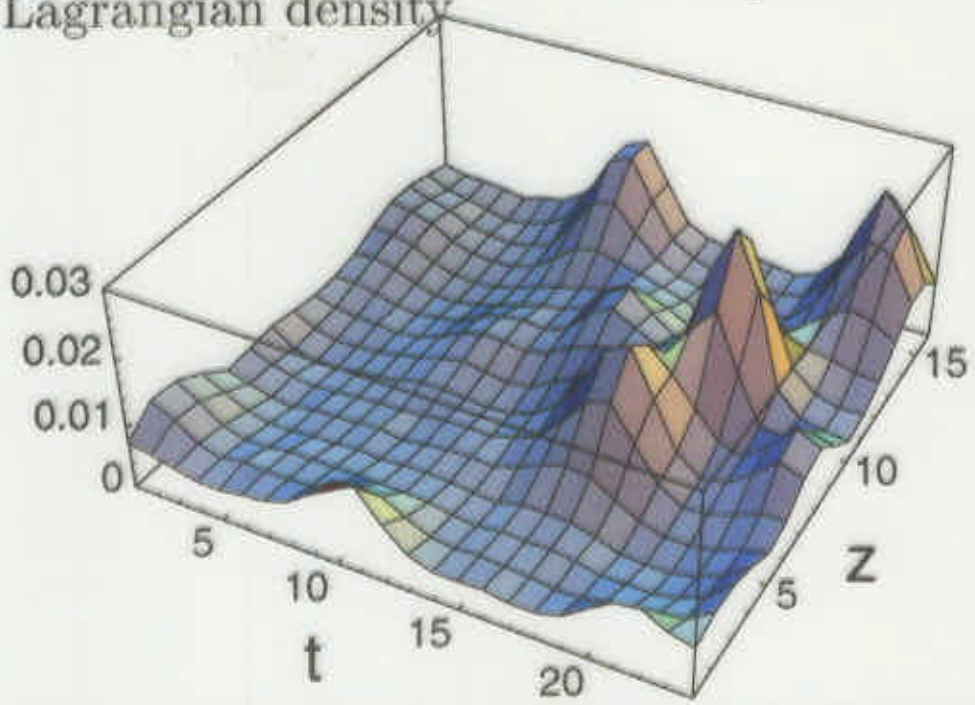
Experimental discovery would be novel non-perturbative evidence for non-Abelian gauge theories.

# Instantons in QCD

Non-perturbative topological fluctuations of gauge fields in time and space

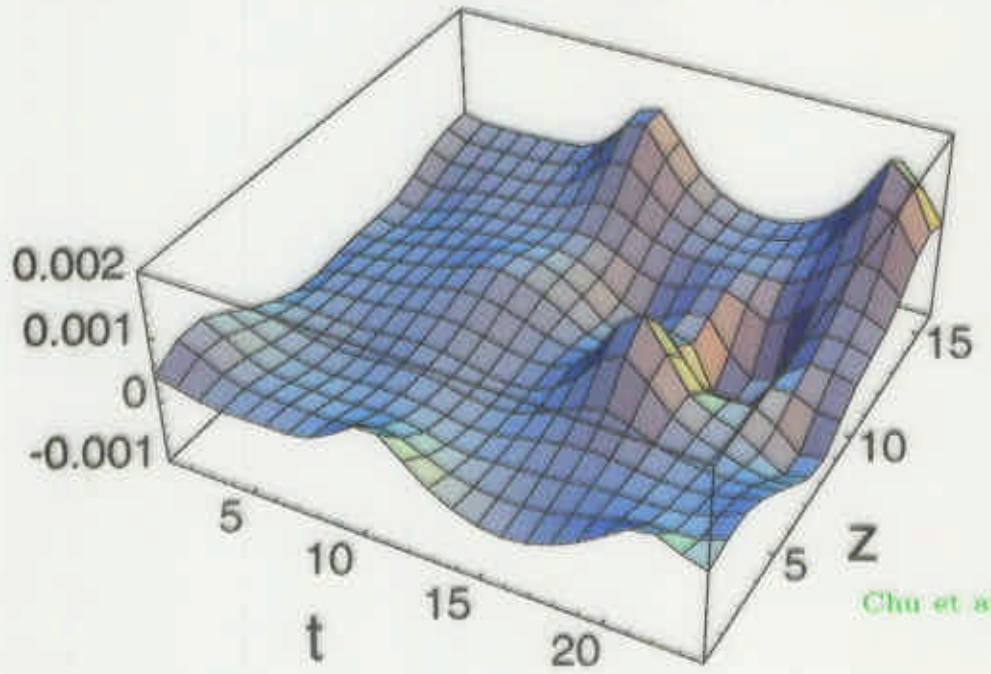
Snapshot of the QCD vacuum

Lagrangian density



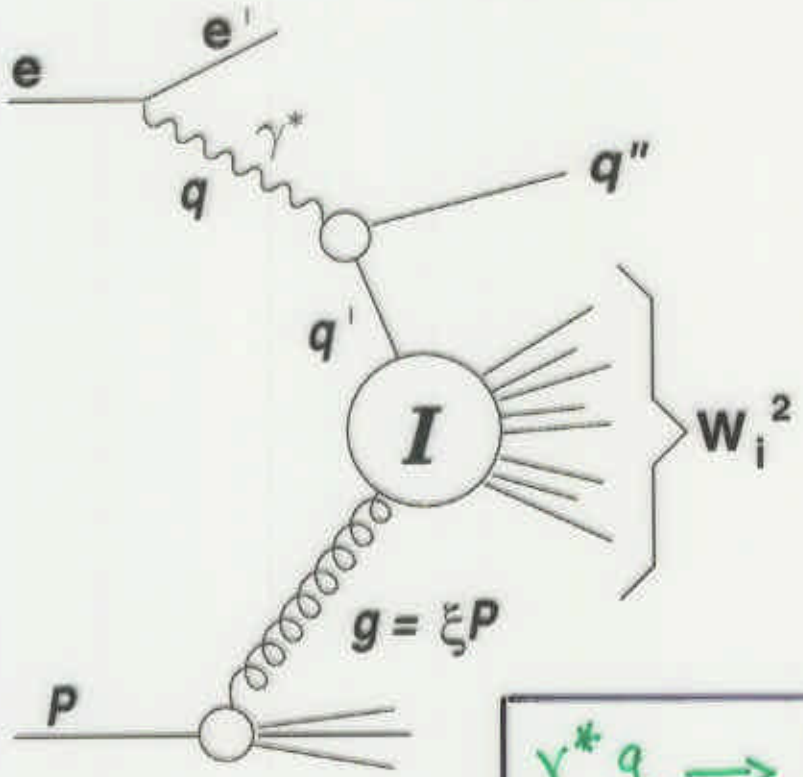

$(n_f = 0)$

Topological Charge: $Q = \frac{\alpha_S}{2\pi} \int d^4x \, \frac{1}{2}\mathrm{tr}(F_{\mu\nu}\tilde{F}_{\mu\nu}) = \pm 1, \pm 2, \ldots$




Chu et al. PRD 49 (1994) 6039

# Instantons in DIS




Variables of I-subprocess:

$$Q'^2 = -q'^2 = -(q - q'')^2$$

$$x' = Q'^2 \,/\, (2\, g \cdot q')$$

$$W_i^2 = Q'^2\,(1 - x')/x'$$

experimentally:
difficult or impossible
to reconstruct/cut

$$\gamma^* g \longrightarrow \sum_f (q_R + \bar{q}_R) + n_g\, g \qquad \tilde{n}_g \sim 3\text{-}4$$

- Instanton-induced events produced in quark-gluon fusion
  Theory and phenomenology ⟶ Ringwald&Schrempp
- DIS: large $Q'^2$ selects small-size I's → I-pert.theory valid
- Implemented in QCDINS Monte Carlo (R&S, paper#251, this conf.)
- Cross section prediction order $10 - 100$ pb
  Expect sizeable number of events
  but background O(100-1000) larger

# Comparison to Lattice calculations

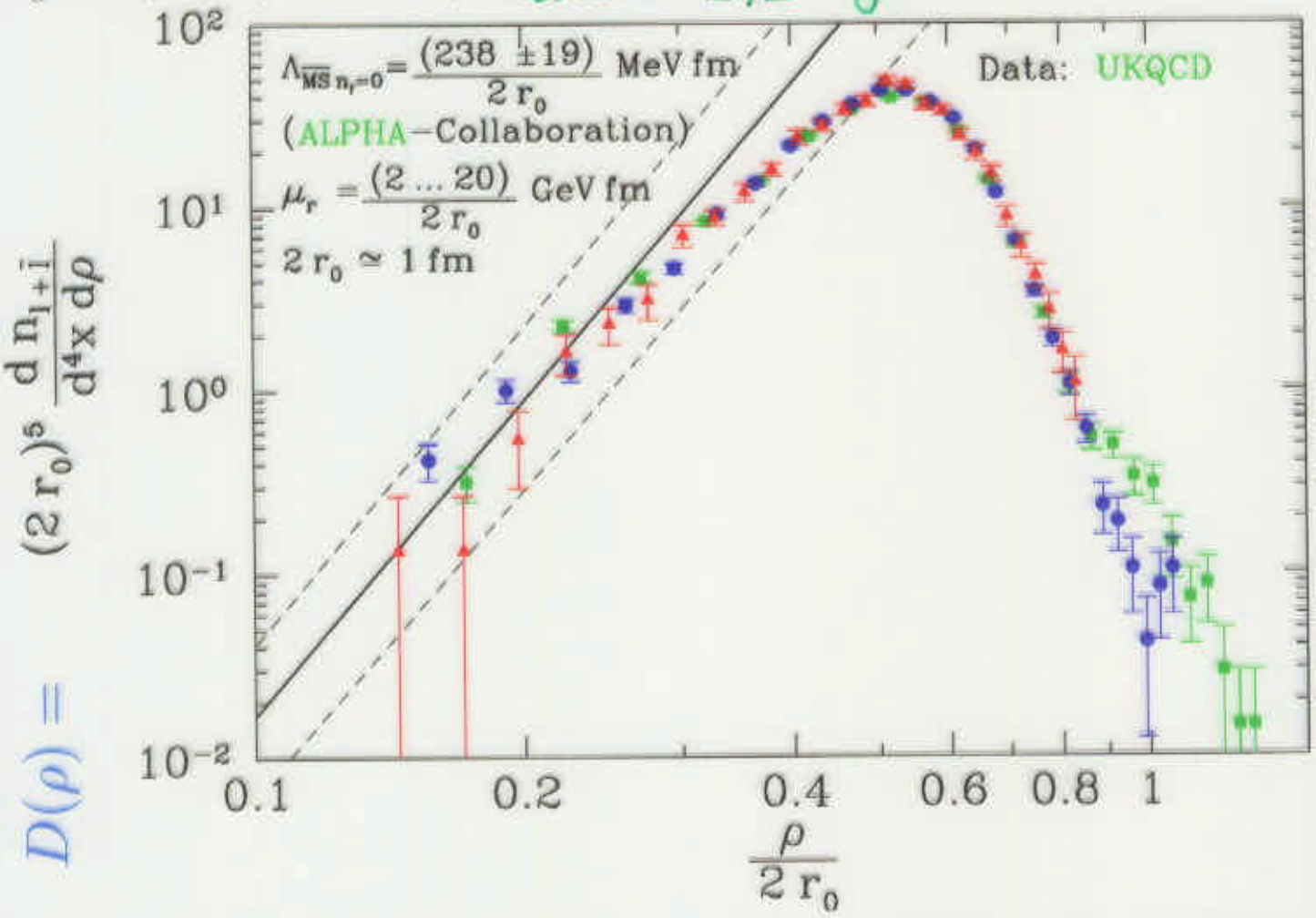


See Ringwald&Schrempp, paper #255 this conf.

QCD lattice vacuum fluctuations calculated in Euclidean $(\vec{x}, t)$, $n_f = 0$

Extract fiducial region $(\rho, R)$ or $(Q'^2, x')$ where I-perturb. theory is valid

($\rho$=size, $R = I, \bar{I}$ distance) dilute $I, \bar{I}$ "gas"




Agreement in shape and normalisation (!) for $\frac{\rho}{2\, r_0} \lesssim 0.35$

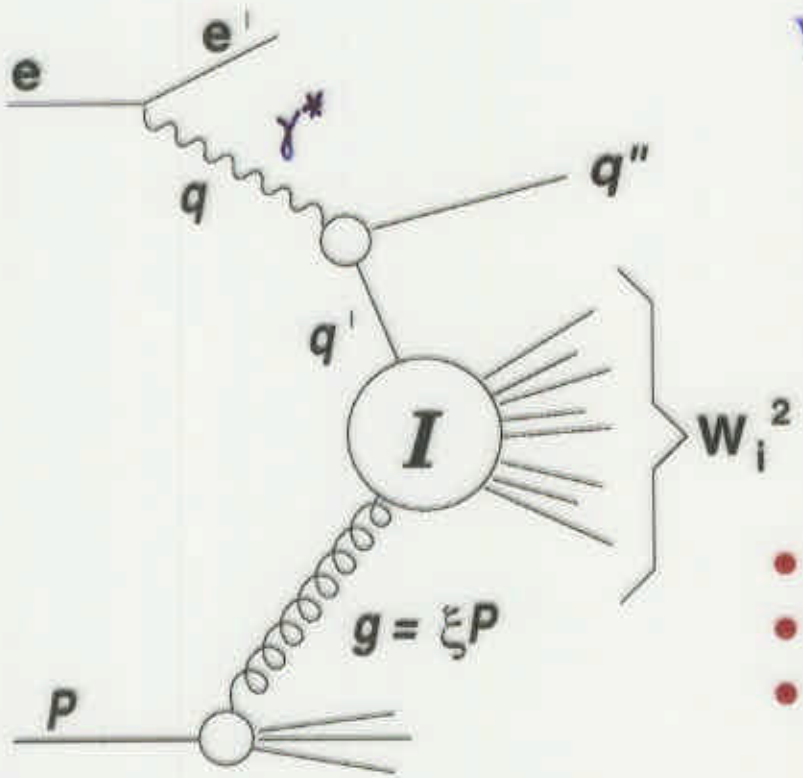
Error band due to uncertainty in $\Lambda^{(n_f=0)}_{\overline{MS}}$

$$\rho \Lambda^{(n_f=0)}_{\overline{MS}} \leq 0.42 \quad \leftrightarrow \quad Q' / \Lambda^{(n_f)}_{\overline{MS}} \geq 30.8$$

$$R/\rho \geq 1 \quad \leftrightarrow \quad x' \geq 0.35$$

For $Q^2 > 113$ GeV$^2$, $0.1 < y < 0.9$ : $\sigma^{(I)}_{HERA} = 29^{+10}_{-7.5}$ pb

# Experimental Signature




Variables of I-subprocess:

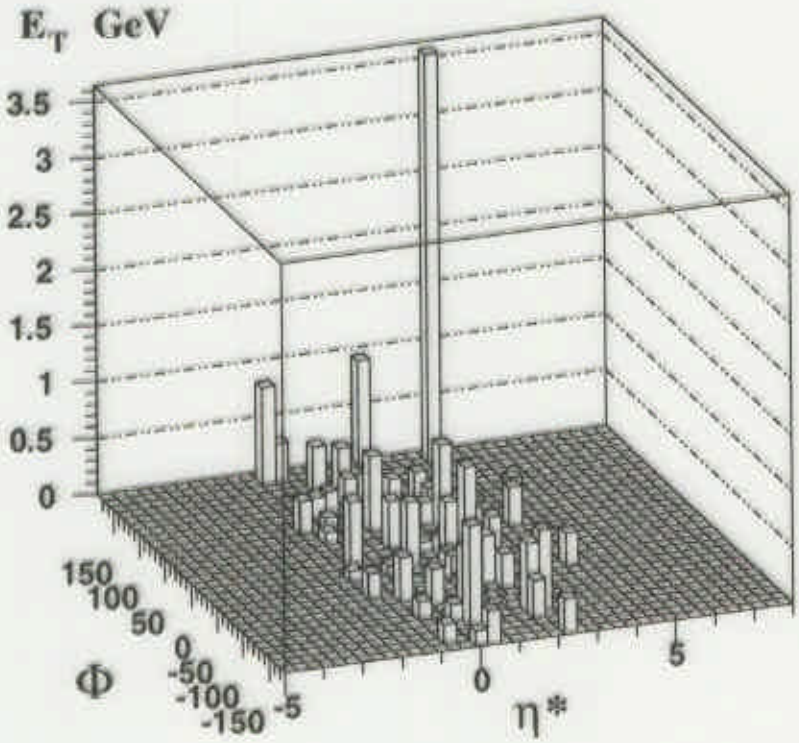
$Q'^2 = -q'^2$

$x' = Q'^2 \,/\, (2\, g \cdot q')$

$W_i^2 = Q'^2\,(1 - x'\,)/x'$

- hard jet
- $Q'^2$ poorly reconstructed
- $x'$ reconstr. impossible

'Typical event'
$(\eta, \phi)-$plane: hadronic CMS




- Densily populated narrow band flat in $\Phi$ from isotropic decay in $I-$rest system (central part of detector)

- Large total Et
- Large Multiplicity
- All kinds of flavours

e.g. $K^{\pm}$, $\Lambda$
$\rightarrow$ flavour tagging now under study

# DIS Event Selection

H1 data 1997: $\int \mathcal{L} = 15.78\ \mathrm{pb}^{-1}$

- Phase space cuts:

$\theta_{el} > 156°, \quad 0.1 < y_{el} < 0.6, \quad x_{el} > 10^{-3}$

- Technical cuts:

Scattered electron in H1 backward calorimeter
with $E_{el} > 10$ GeV,
$-30\ \mathrm{cm} < z_{vtx} < 30\ \mathrm{cm}$
$35 < \sum E - P_z < 70\ \mathrm{GeV}$

- Hadronic Final State Objects:

Presence of charged particles in region of acceptance of Central Track Chambers:
$20° < \theta < 155°$, $p_T > 0.15$ GeV
and
combination of Tracks and Calorimeter clusters to measure particle-energy flow

- Data sample $\sim$ 275k events

# Six Observables

Find highest $E_T$ jet ("current jet"): cone algorithm, $R = 0.5$

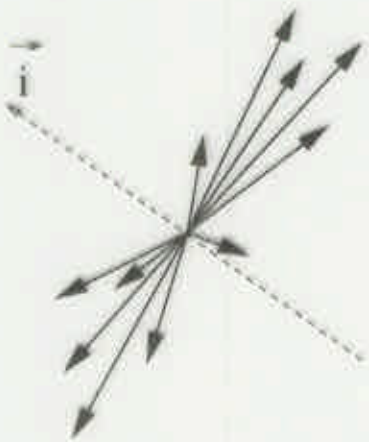
- Transverse energy of jet: $Et_{\rm jet}$ in hCMS
- Virtuality of quark entering I-subprocess: $Q'^2$

Remove particles in current jet to define band in $\eta$:

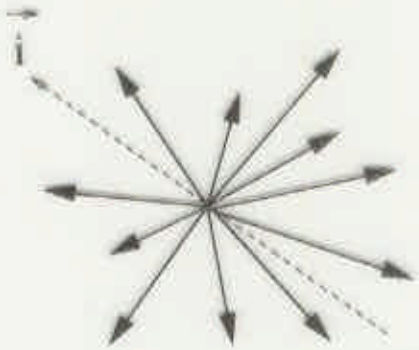
With $\bar{\eta} = \sum_h Et_h\, \eta_h / \sum_h Et_h$: define band as $\bar{\eta} \pm 1.1$

- $n_b$: Charged particle multiplicity in band
- $Et_b$: Total transverse energy in band
- Sph: Sphericity in rest-frame particles not in current jet.
- $\Delta_b = (E'_{in,b} - E'_{out,b}) \,/\, E'_{in,b}$

$$E_{out} = \min \sum_{n\ Hadr.} |\, \vec{p_n} \cdot \vec{i}\,|$$
$$E_{in} = \max \sum_{n\ Hadr.} |\, \vec{p_n} \cdot \vec{i}\,|$$



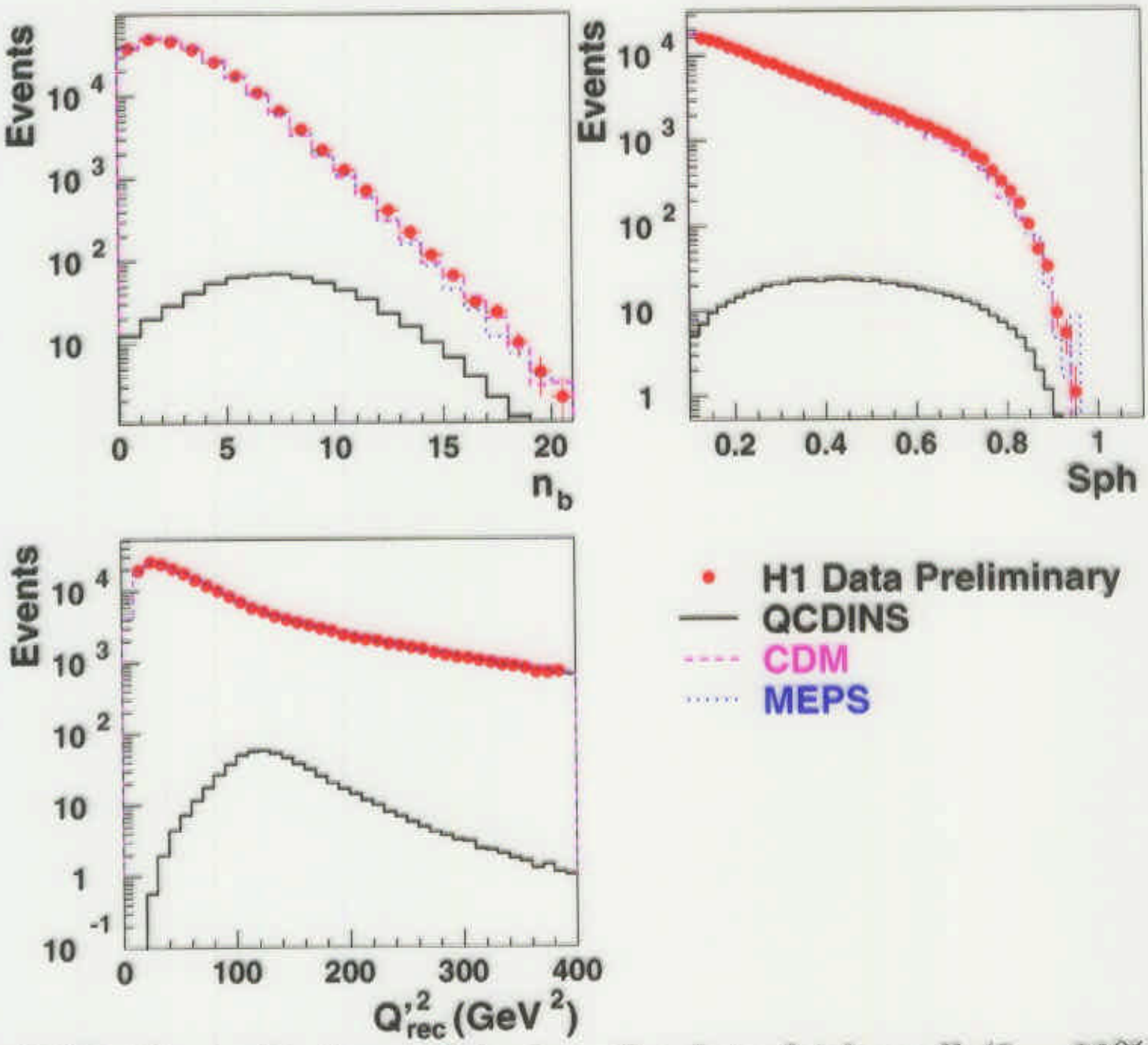

$\Delta_b \approx 1$




$\Delta_b \approx 0$

measure of isotropy

# Distributions before Cuts



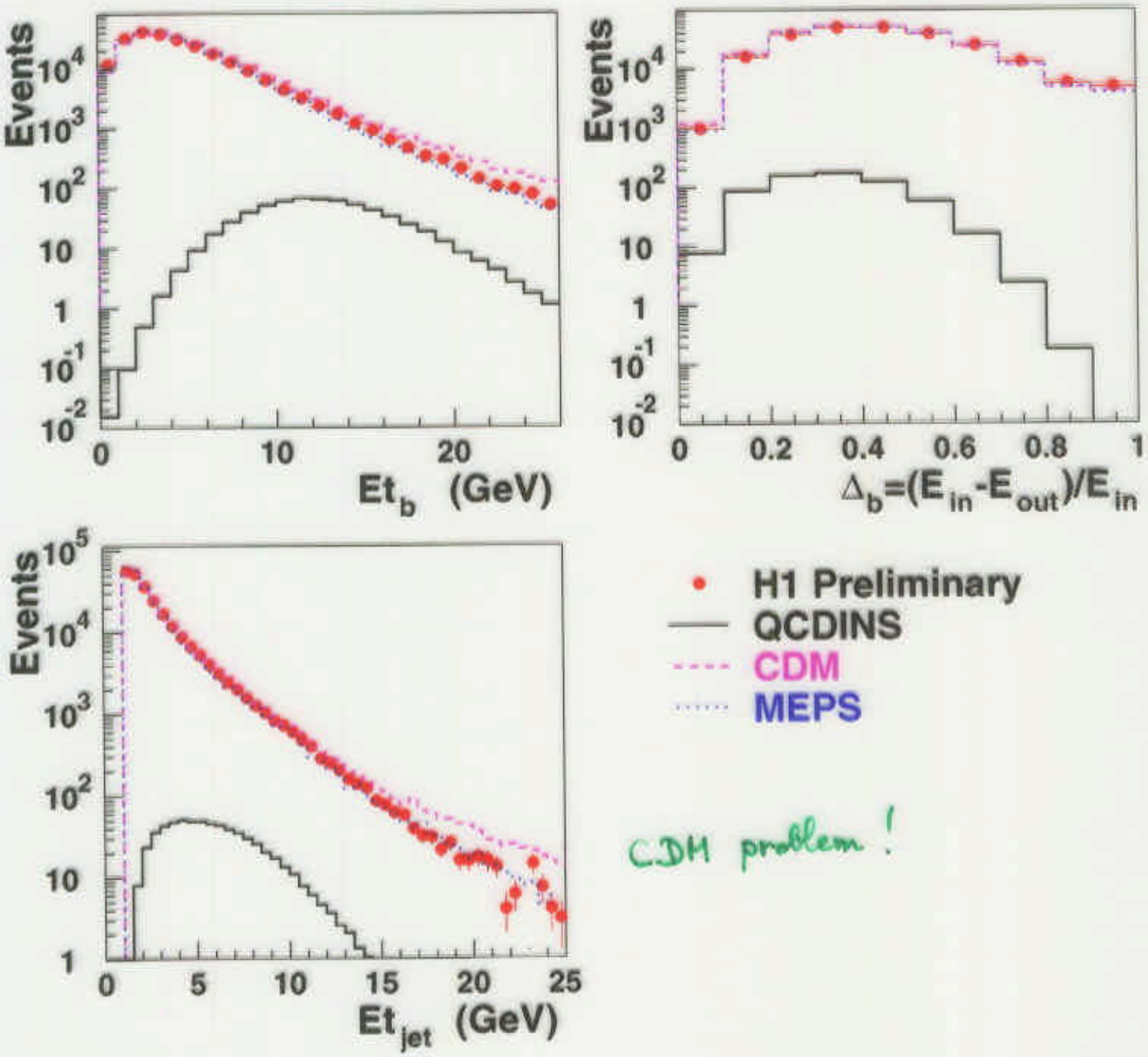

QCD Monte Carlo models describe data fairly well (5 – 20%)

Expected I-signal O($10^2$ – $10^3$) below "background"

- CDM: Color Dipole Model $\longrightarrow$ ARIADNE
- MEPS: Matrix Element + Parton Showers $\longrightarrow$ RAPGAP

# Distributions before Cuts

Observables not used in cuts



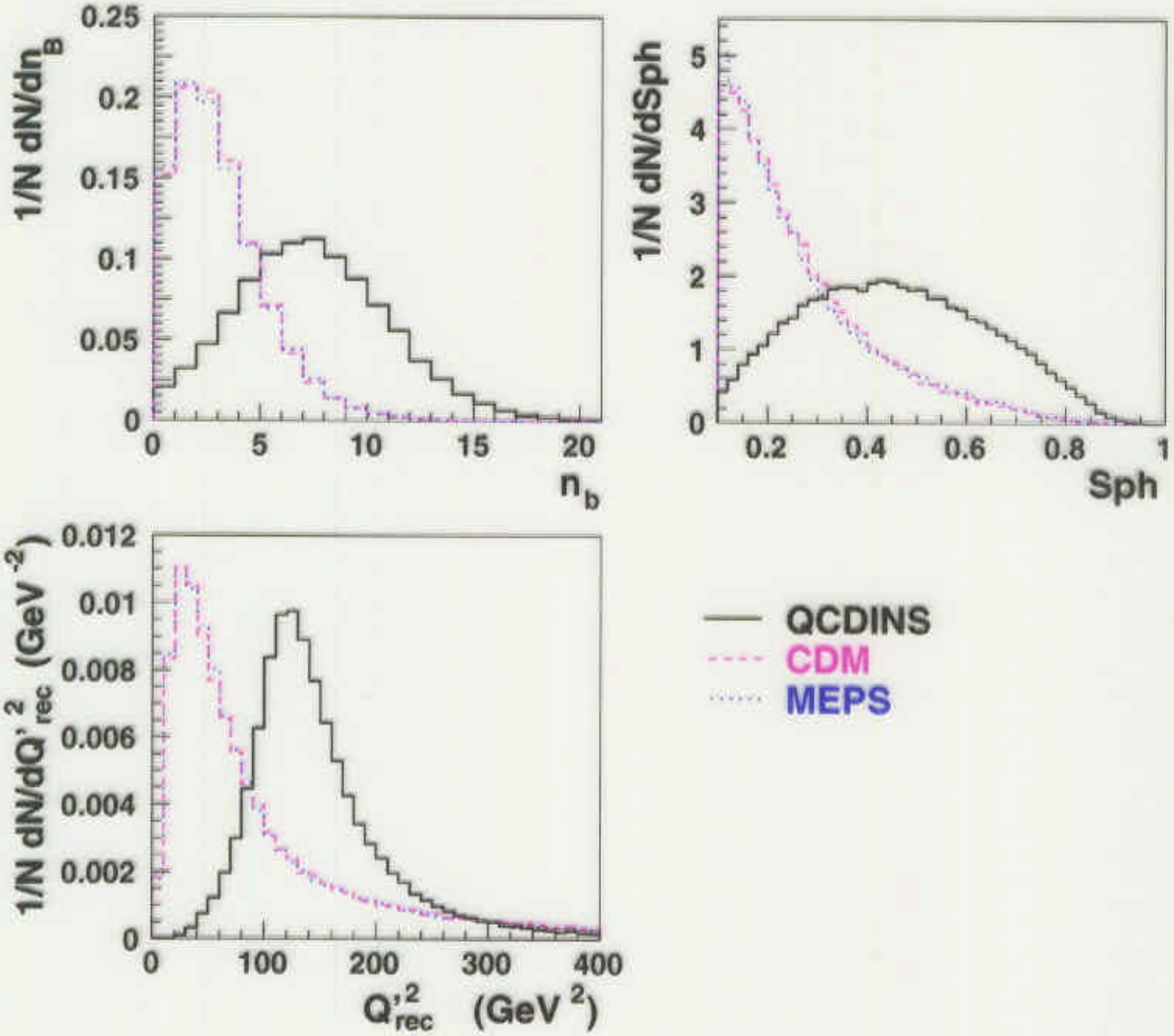

QCD Monte Carlo models describe data quite well (5 – 20%)

Expected I–signal O($10^2$ – $10^3$) smaller than "background"

# Search Strategy



## Shape-normalized distributions




Large differences "normal DIS" ⇔ QCDINS used to find optimized selection cuts

# Selection of Cut Scenario

Cut values:

$n_b \geq$ 5 6 7 8 9

Sph $\geq$ 0.4, 0.5, 0.55, 0.6, 0.65

95, 100, 105, 110, $115 < Q'^2 < 200$ GeV$^2$

in total 125 combinations !

Define cut-scenario on basis of instanton efficiency and separation power

| Scen ario | Cuts $Q'^2$ ( GeV$^2$) | Sph | $n_b$ | $\epsilon_{ins}$ | $\frac{\epsilon_{ins}}{\epsilon_{DIS}}$ CDM | $\frac{\epsilon_{ins}}{\epsilon_{DIS}}$ MEPS |
|---|---|---|---|---|---|---|
| A | 95.0-200.0 | 0.40 | 5 | 32 % | 35 | 34 |
| B | 105.0-200.0 | 0.40 | 7 | 21 % | 56 | 52 |
| C | 105.0-200.0 | 0.50 | 8 | 11% | 86 | 71 |

↓ % I-signal after cuts

Scenario A: Highest instanton efficiency ($\epsilon_{ins}$)

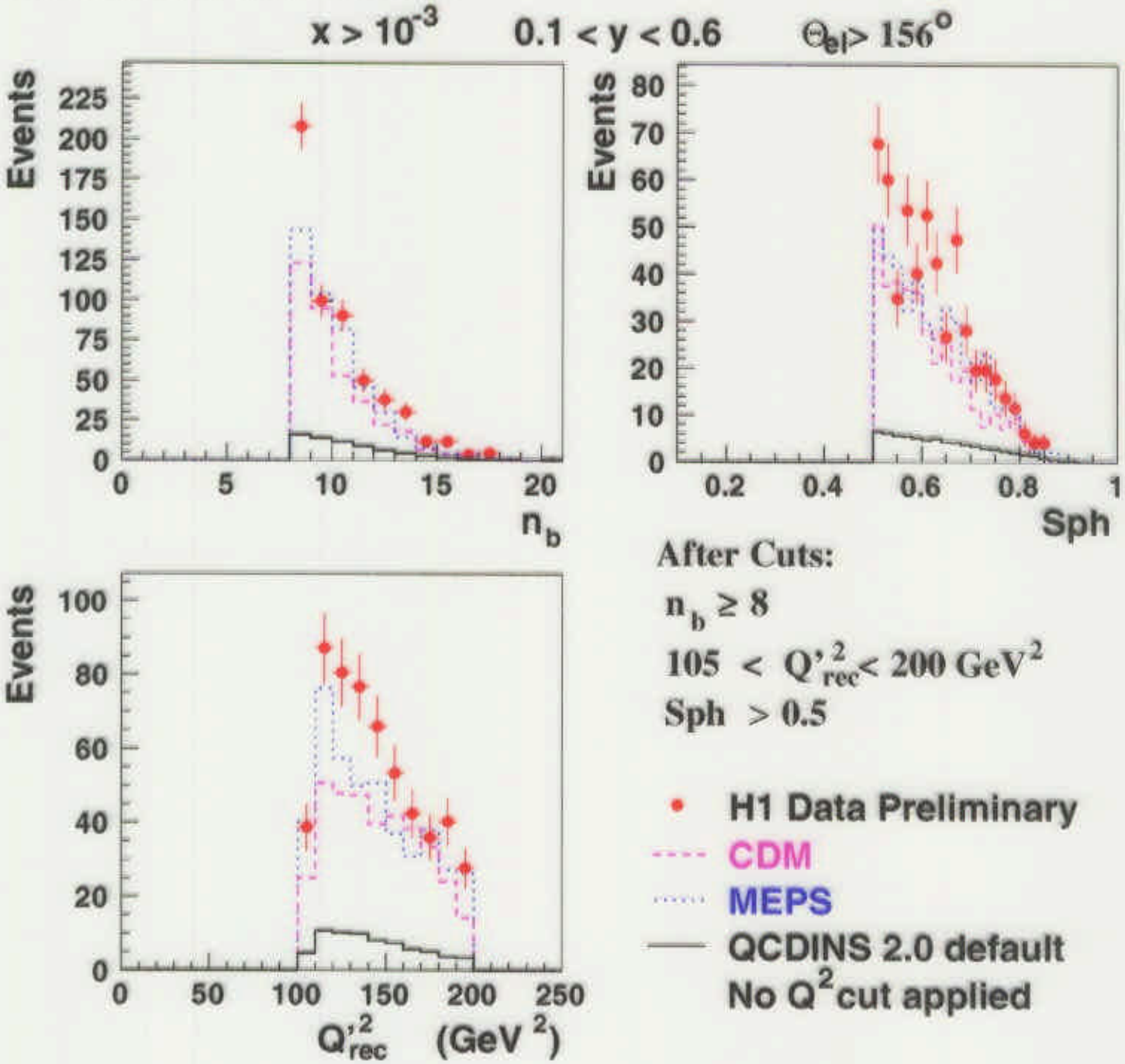
Scenario B: High $\epsilon_{ins}$ at reasonable separation power ($\frac{\epsilon_{ins}}{\epsilon_{DIS}}$)

Scenario C: Highest separation power at $\epsilon_{ins} > 10\%$

**Here: concentrate on Scenario C**

# Distributions after Cuts C

Observables used in cuts




Background reduction by factor $\sim 600 - 800$

In some regions excess of events compared to CDM/MEPS

549 events measured

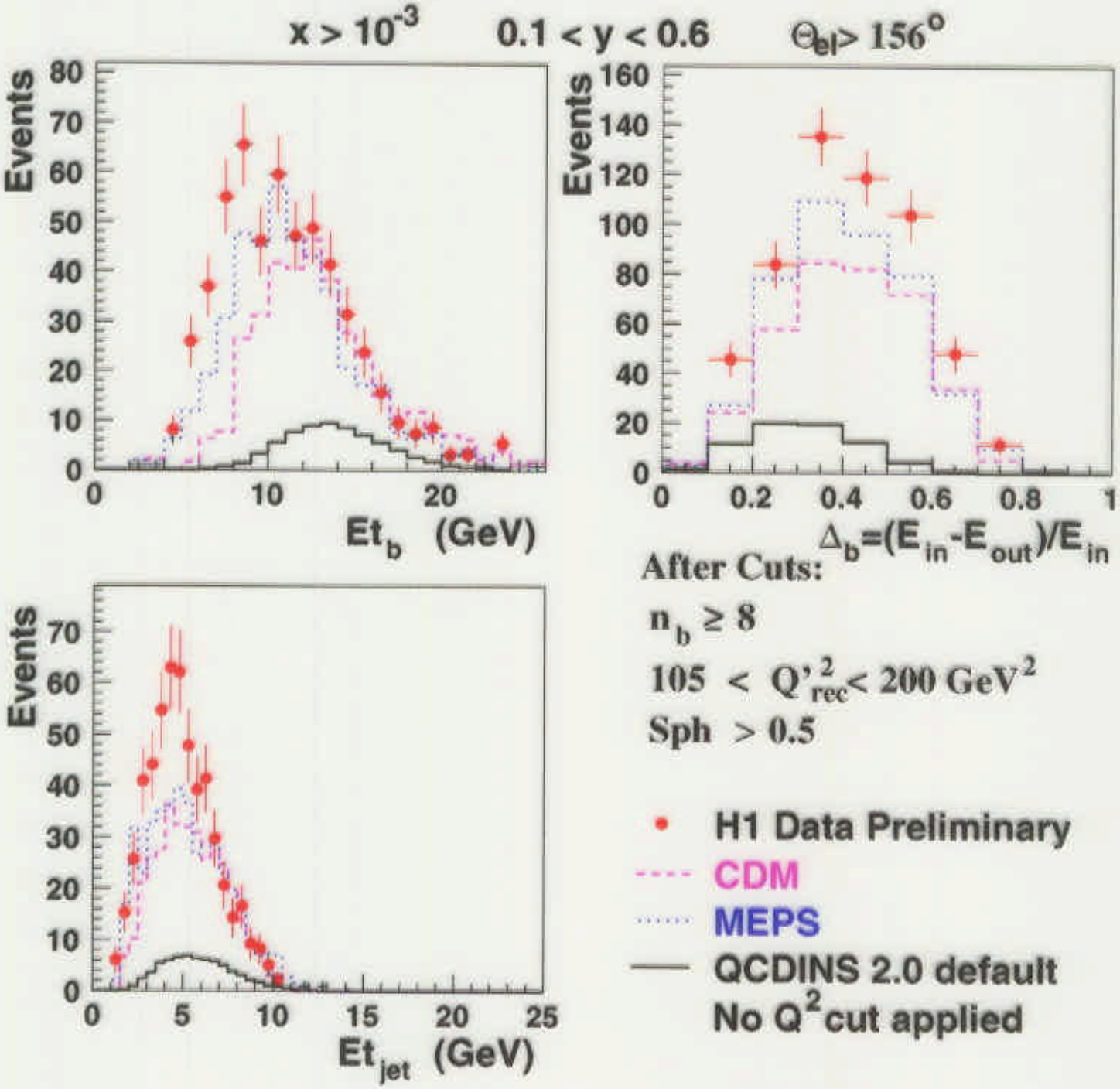
$363^{+22}_{-26}$ (CDM) and $435^{+36}_{-22}$ (MEPS) expected

Expected instanton signal $\sim$ discrepancy data and CDM/MEPS

→ Tails!

# Distributions after Cuts C

Observables not used in cuts

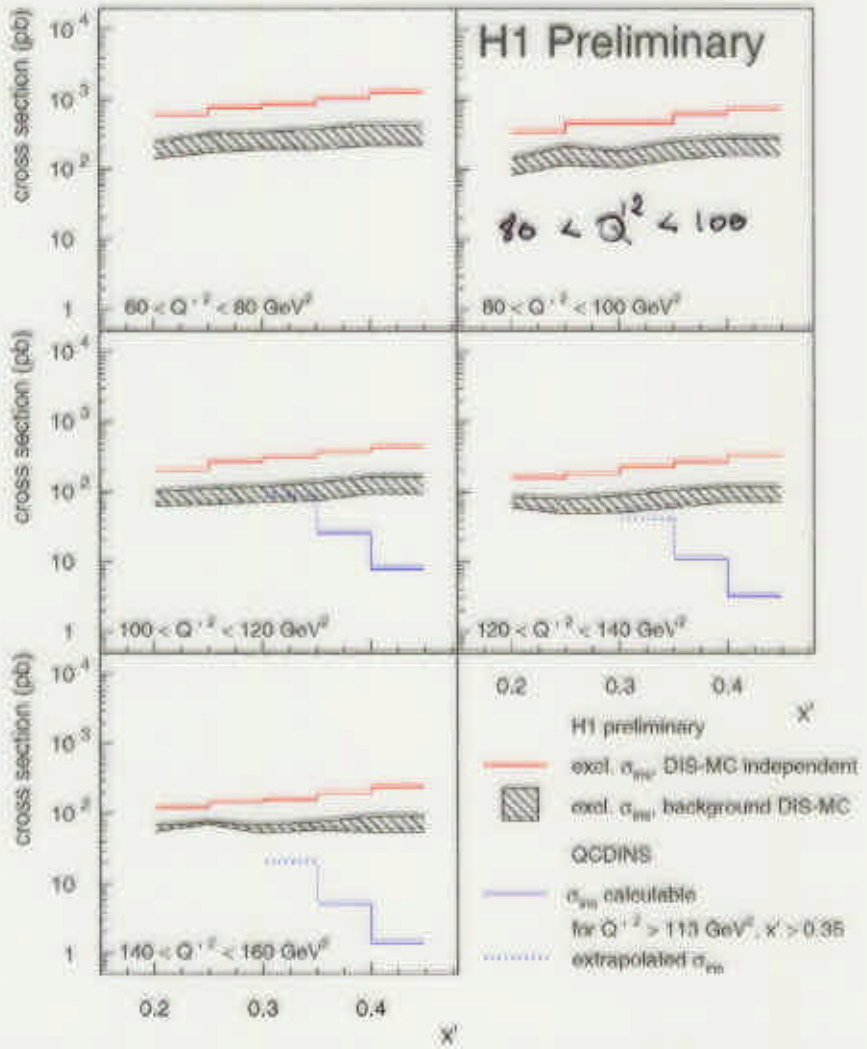



Shape of the spectra of observables not used to cut is not well reproduced in CDM and MEPS

Event excess in $E_{t_b}$ not quite as expected from QCDINS, but ...
QCDINS cannot be excluded given
the uncertainties in $\sigma^{(I)}$, I-hadronisation and DIS modelling

# Cross Section Upper Limits

$x > 10^{-3}$, $0.1 < y < 0.6$, $\Theta_{el} > 156^{\circ}$




- Red Lines: Upper limit assuming standard-DIS $\sigma = 0$
- Bands: Upper limit from difference data and CDM/MEPS
- Exclude $\sigma^{(I)} \sim 100 - 1000$ pb

# Summary

- H1 searched for I-induced DIS events predicted to be measureable at HERA (Ringwald&Schrempp).
- Search strategy optimised to exploit the characteristics of instanton-induced processes, (but) based on QCDINS Monte Carlo.
- For $n_b \geq 8$, $105 \leq Q'^2 \leq 200$ GeV$^2$, Sph $\geq 0.5$:
  549 events found in the data,
  $363^{+22}_{-26}$ (CDM) and $435^{+36}_{-22}$ (MEPS) are expected,
  Qualitative similarity between observed excess and shape predicted by QCDINS for 3 variables used in cuts.
- But... predicted instanton cross section is at the level of the difference between the pQCD models (CDM/MEPS)
- Shape of three other discriminating variables not used in cuts not well reproduced by CDM or MEPS

  Excess in data not really as expected from I-signal distribution but no definitive conclusions given uncertainties in theoretical $\sigma^{(I)}$ and in standard pQCD Monte-Carlo's.
- Experimental upper limits (100 – 1000 pb) exclude rapid rise of $\sigma^{(I)}$ with $\rho$ as would follow from naive extrapolation of I-perturbation theory. **Consistent with lattice results!**
- Future: multidimensional analysis, flavour-tags, ...