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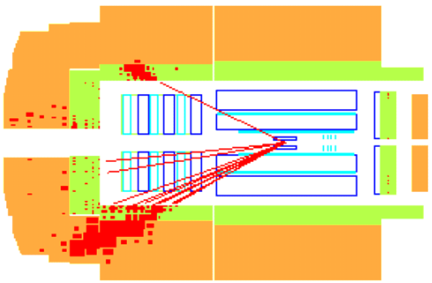
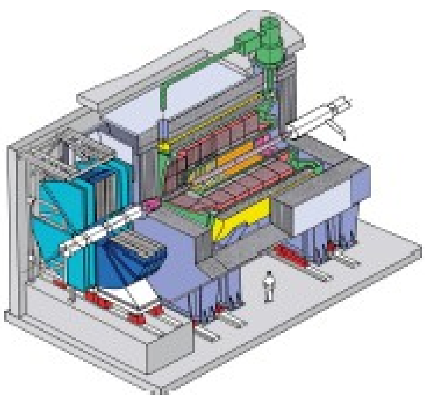
Search for QCD Instantons at HERA

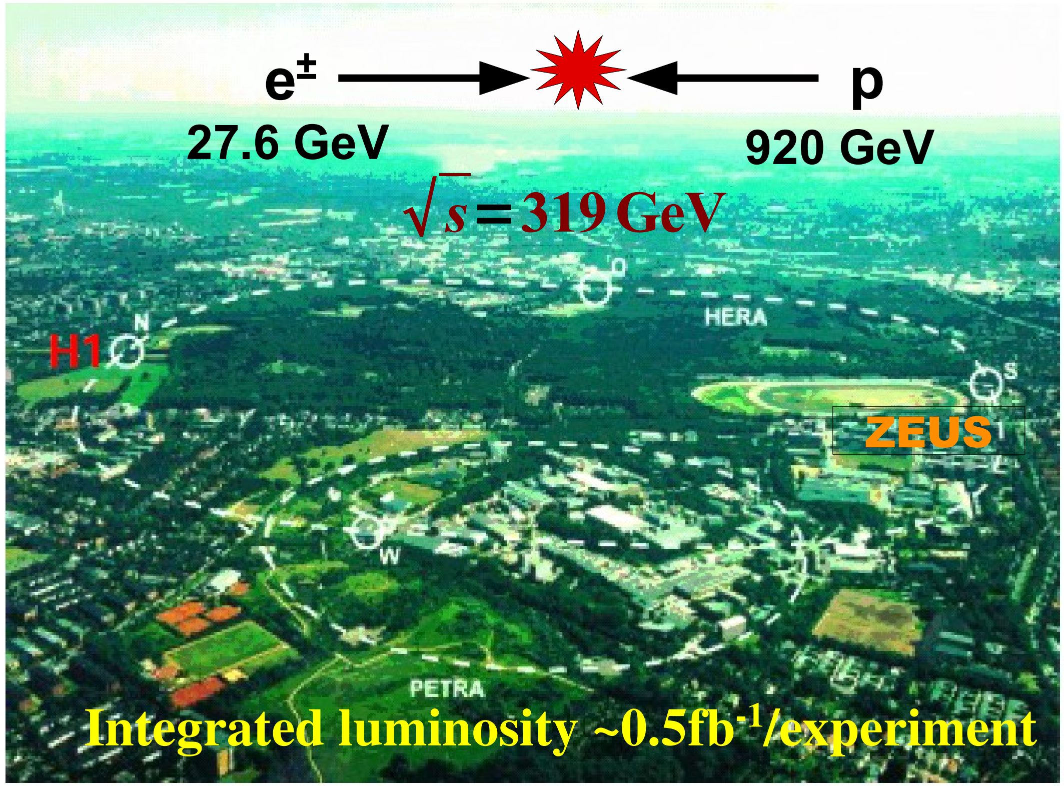
Stanislaw Mikocki
Institute of Nuclear Physics PAN Cracow
on behalf of the H1 Collaboration

Herzog & de Meuron

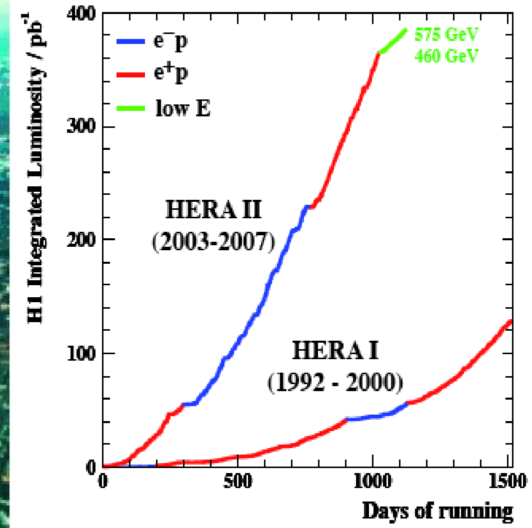
The H1 Experiment at HERA







HERA operation



- Unique ep collider 1992-2007
- Two collider experiments: H1 and ZEUS
- Collected data

  ~100 pb^{-1} (HERA-I)

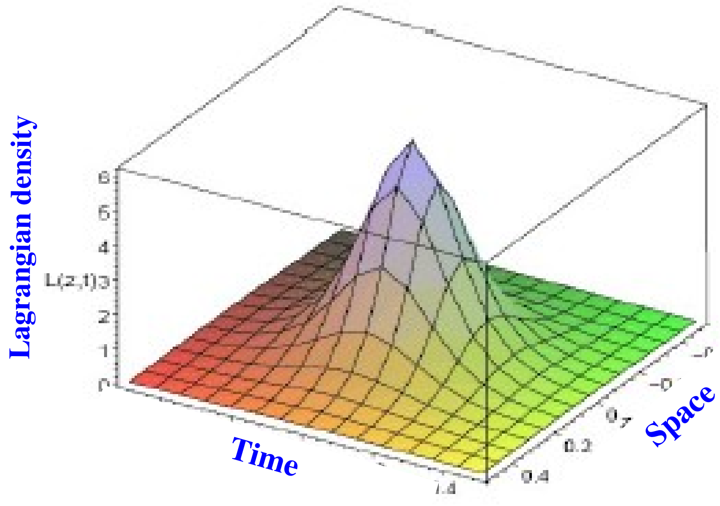
  ~400 pb^{-1} (HERA-II)
- This analysis: HERA-II data

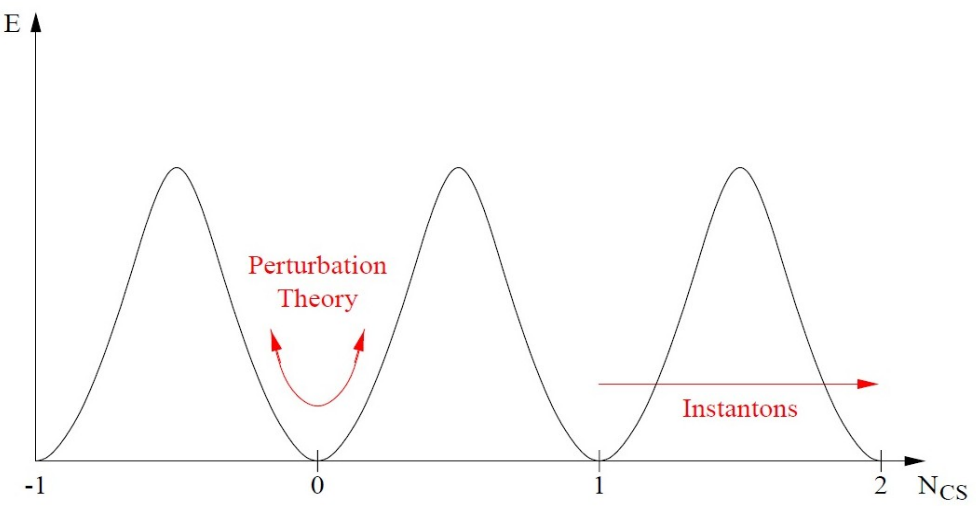
Instantons

- **Instantons: non-perturbative fluctuation of the gauge fields**
- **In Standard Model, instantons induce anomalous processes violating conservation of baryon and lepton number in EW theory and chirality in QCD**
- **Instanton interpretations:**

  - localized *pseudoparticle* in space and time (euclidean space) or as

  - tunnelling *process* (Minkowski space) between topologically non-equivalent vacua



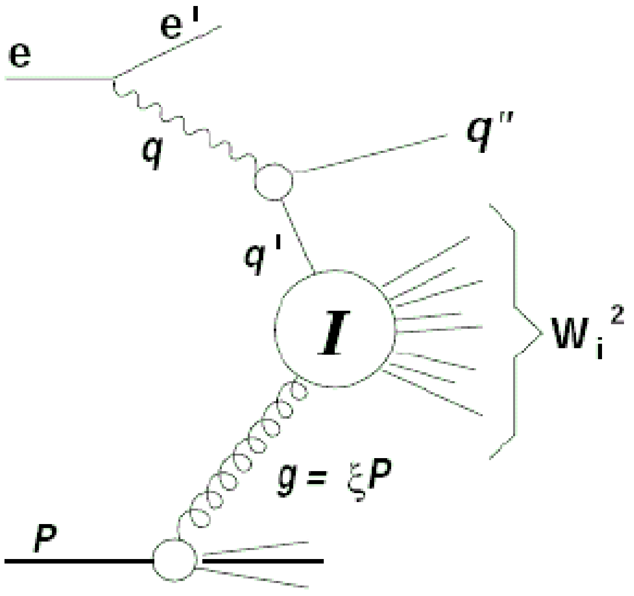


Cross-section for instanton induced processes is exponentially suppressed

$\sigma \sim e^{-4\pi/\alpha}$ (α - relevent coupling constant)

QCD Instanton in DIS at HERA

- **Instanton-induced events produced in quark-gluon fusion**
- **Theory and phenomenology worked out by A.Ringwald and F.Schrempp and implementation in QCDINS Monte Carlo generator makes full event topology available**



Sizeable cross section in recommended phase space:

$$0.1 < y < 0.9\,,\quad Q^2 > Q'^2_{min} \approx 113\ \mathrm{GeV}^2\,,\quad x' > x'_{min} \approx 0.35$$

$$\text{Prediction}: \sigma^{(I)} \approx 25 - 30\ \mathrm{pb}$$

Variables of I-subprocess:

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

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

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

This analysis:

$$150 < Q^2 < 15000\ \mathrm{GeV}^2\,,\quad 0.2 < y < 0.7$$

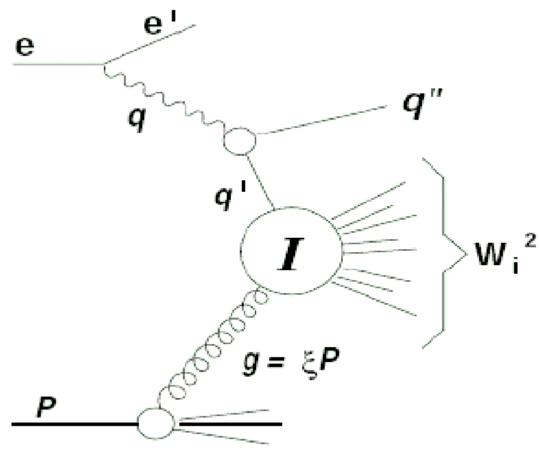
$$Q'^2 > 109\ \mathrm{GeV}^2\,,\quad x' > 0.35$$

$$\sigma^{(\mathrm{I})} = 10 \pm 3\ \mathrm{pb}$$

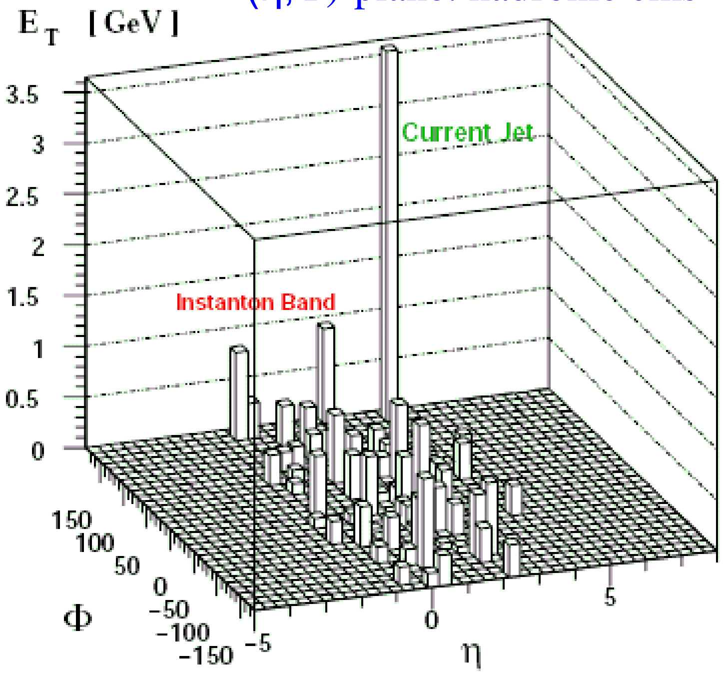
cross section uncertainty by varying QCD scale : $\Lambda_{\overline{MS}}^{n_f=3} = 339 \pm 17\ \mathrm{MeV}$

S. Moch, A. Ringwald, F. Schrempp, Nucl Phys. B 507 (1997) 134 [hep-ph/9609445],
A. Ringwald, F. Schrempp, Phys. Lett. B 438 (1998) 217 [hep-ph/9806528],
A. Ringwald, F. Schrempp, Phys. Lett. B 459 (1999) 249 [hep-ph/9903039].
http://www.desy.de/~t00fri/instanton.html
I. I. Balitsky, V.M. Braun Phys. Lett. B 314 (1993) 237 [hep-ph/9305269]

QCD Instanton at HERA : Expected Signature



"Typical event"
(η,Φ)-plane: hadronic cms



- **Hard "current" jet q''**
- **Densely populated narrow I-band**
- **Isotropy in instanton rest frame**
- **High multiplicity**
- **Large total Et**

not exploited in this analysis:

- ***chirality violation***
- ***flavour "democracy"***

H1 and ZEUS searches

- **early HERA-I data**
- **No signal observed and upper limits set**
- **Upper limits above theory prediction**

H1: hep-ex/0205078

ZEUS: hep-ex/0312048

This analysis: H1: DESY-16-050 [arxiv:1603.05567]

Events Selection

DIS selection

$150 < Q^2 < 15000$ GeV^2

$0.2 < y < 0.7$

Tracks Selection

$P_T > 0.12$ GeV

$20^o < \theta < 160^o$

Hadronic Final State (HFS):

Charged tracks and calorimeter clusters are attributed to HFS objects which are reconstructed avoiding double counting of energy

Data sample:

~351 pb^{-1}

Jet Selection

Inclusive kT algorithm in HCMS frame

$P_{T,\,jet} > 3$ GeV

***Jets boosted to LAB*:**

$P_{T,\,jet} > 2.5$ GeV

pseudo-rapidity: **$-1 < \eta_{jet} < 2.5$**

Monte Carlos used

Background:

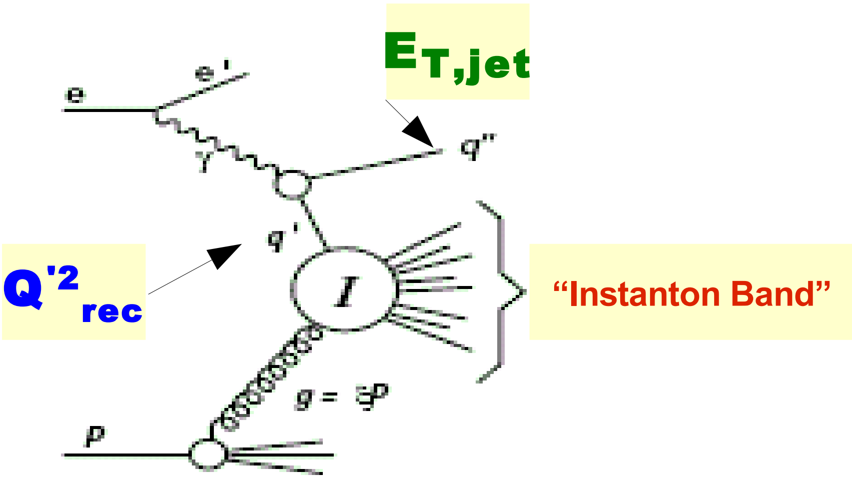
DJANGOH (*CDM*)

RAPGAP [*DGLAP(MEPS)]*

Signal: QCDINS

A. Ringwald, F. Schrempp,[hep-ph/9911516], Comput. Phys. Commun. **132** (2000) 267
http://www.desy.de/t00fri/qcdins/qcdins.html

Strategy and Observables



1. DIS selection
2. In HCMS (γ+P=0)
   - Find current jet → $E_{T,jet}$ and Q'^2_{rec}
     - Remove HFS objects found by jet algorithm
     - Find "instanton band" = <η>±1.1

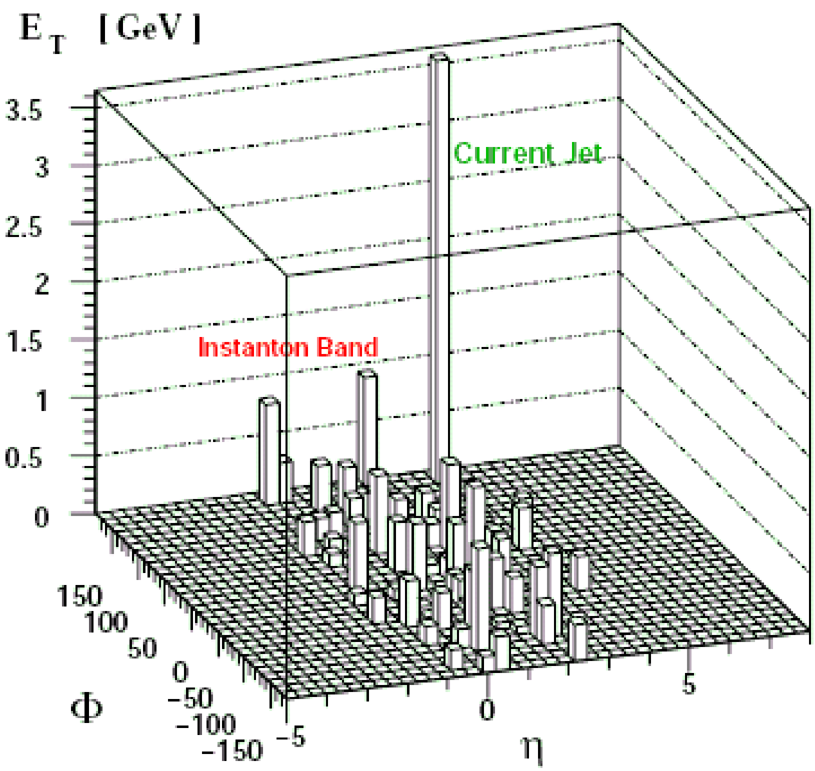
     -> x'
3. Boost HFS objects within "instanton band" into "instanton rest " frame

   q'+ξP=0 , ξ = <ξ> = 0.076
4. For objects in "instanton band " find observables:
   - n_B - number of charged particles
   - $E_{T,B}$ – transverse energy of the band

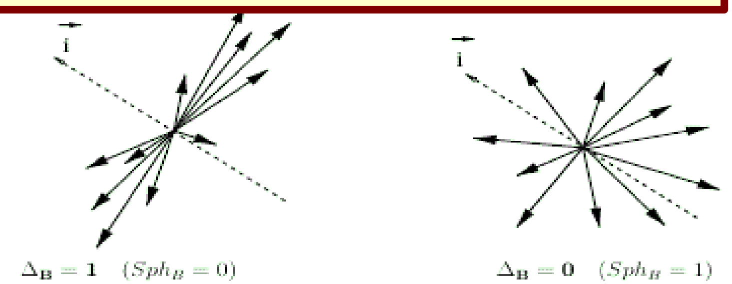
   Topological observables:

   Sphericity, Fox-Wolfram moments,

   Δ_B , E_{in} , E_{out}



Δ_B, E_{in}, E_{out}



$$\Delta_B = (E_{IN} - E_{OUT}) / E_{IN}$$

$$E_{IN} = \sum_h |\vec{p}_h \cdot \vec{i}_{max}|$$

$$E_{OUT} = \sum_h |\vec{p}_h \cdot \vec{i}_{min}|$$

Observables and MultiVariate Analysis (MVA)

Multivariate discrimination technique was used

to reduce "standard" DIS Background and extract expected instanton signal

Five observables selected:

$E_{T,jet}$, n_B , Δ_B , E_{IN} , x'

- **good signal to backgroud separation with good description by MCs**
- **resulting discriminator distribution is well described in background dominated region**

PDERS method was used

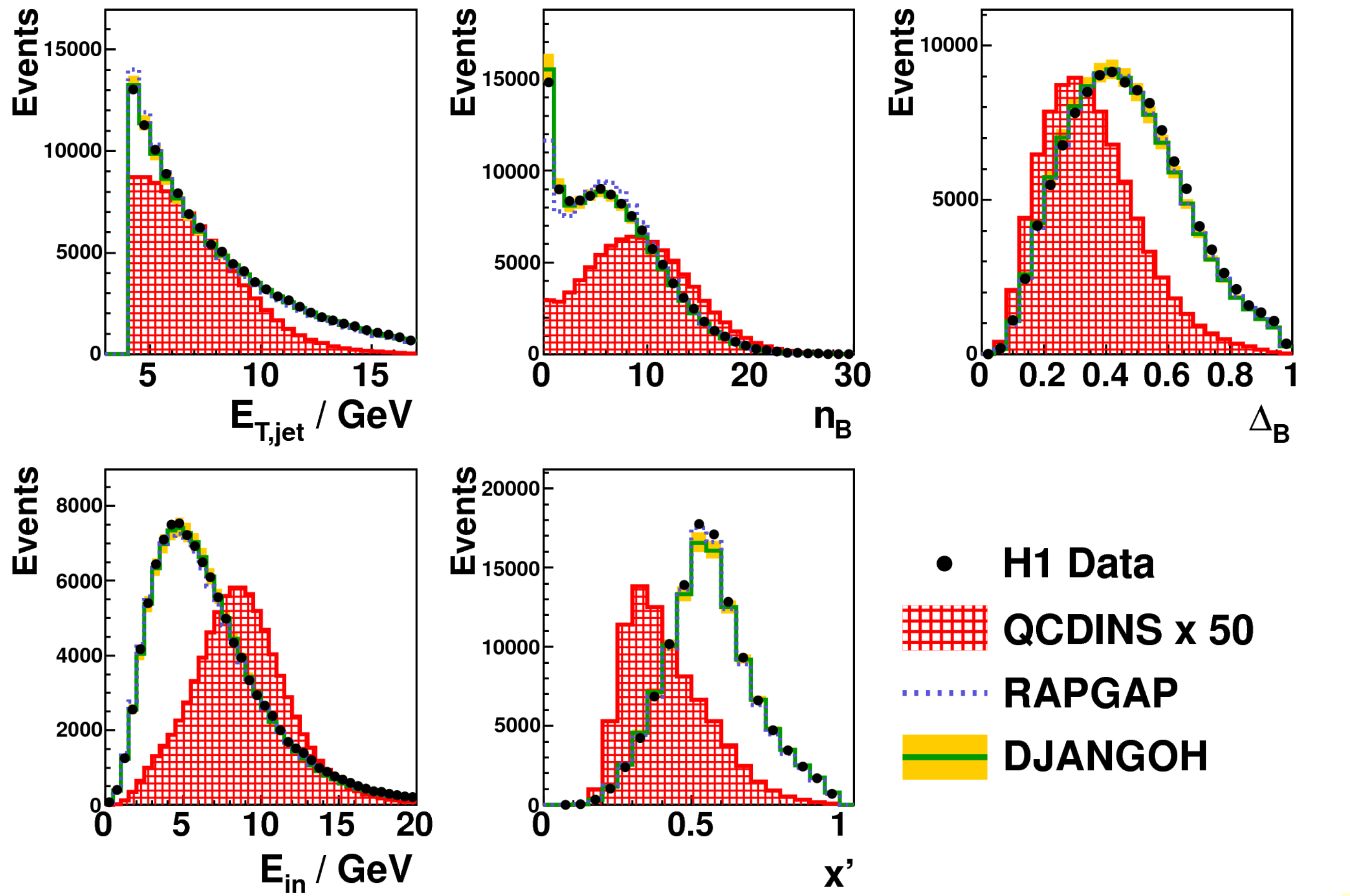
(P*robability Density Estimator with Range Search,ROOT TMVA package*)

Trainning was done with

-QCDINS (signal)

-DJANGOH/RAPGAP (background)

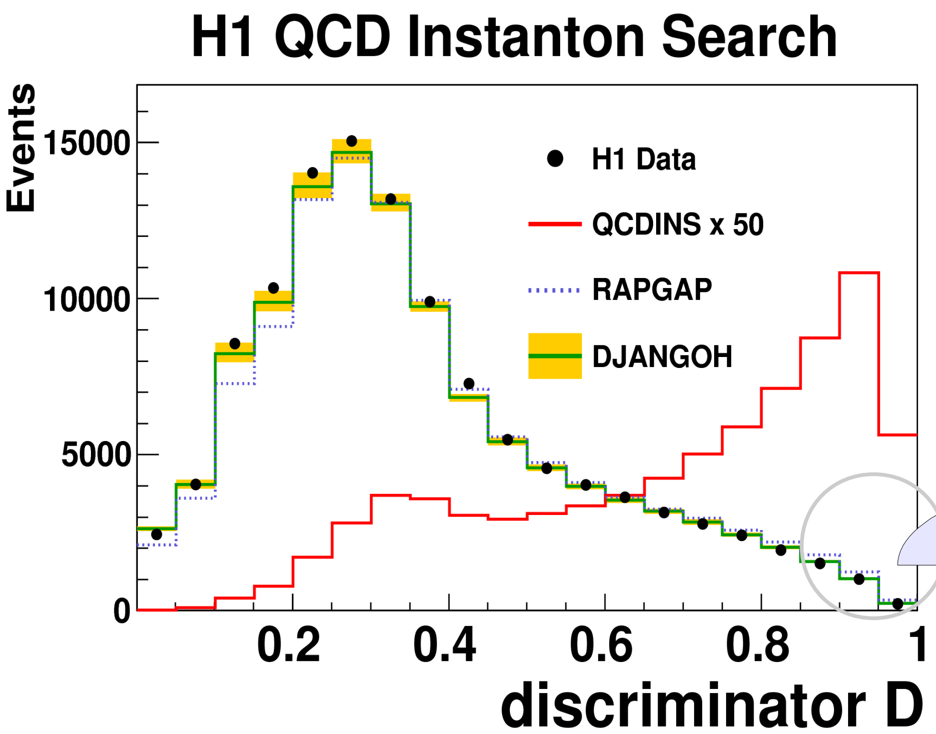
Distributions of Selected Observables for TMVA training



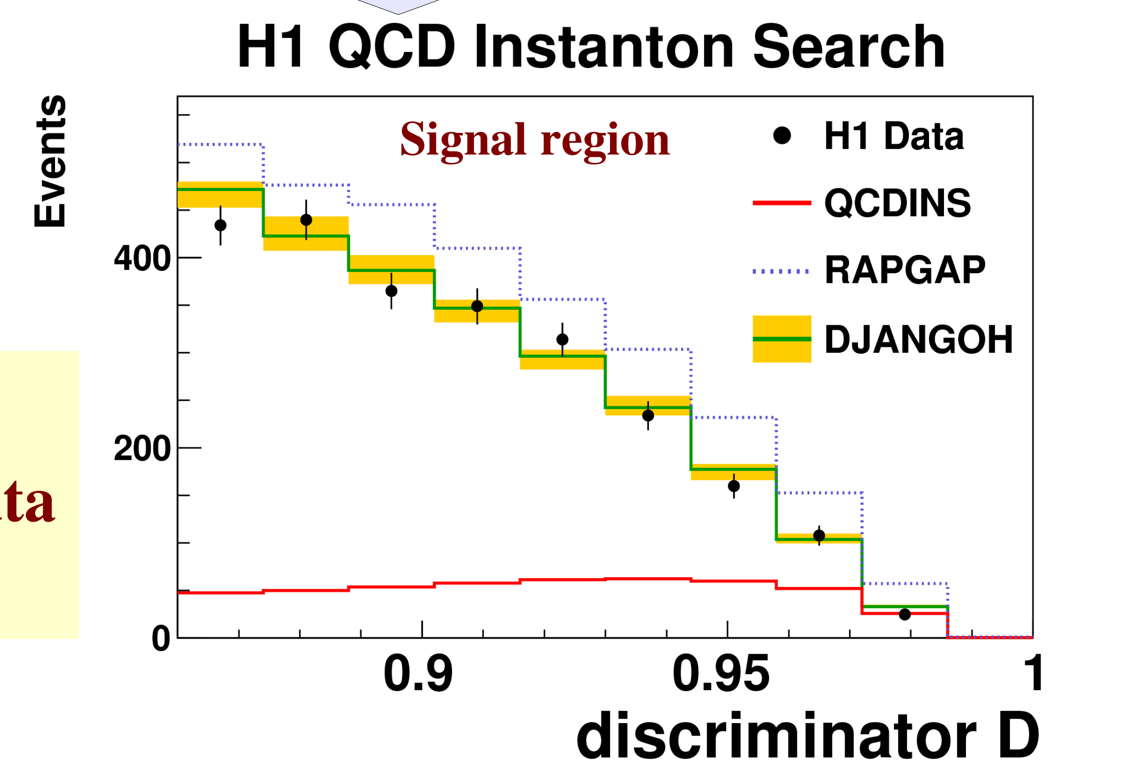
Background models describe data overall within 5-10%

At very low and/or very large values of some observables differences between data and MCs of up to 20%.

PDERS Discriminator Distribution



- Good description of data by DJANGOH in background- and signal regions
- RAPGAP sytematically above data in signal region D>0.86



No signal observed in data

Upper Limit

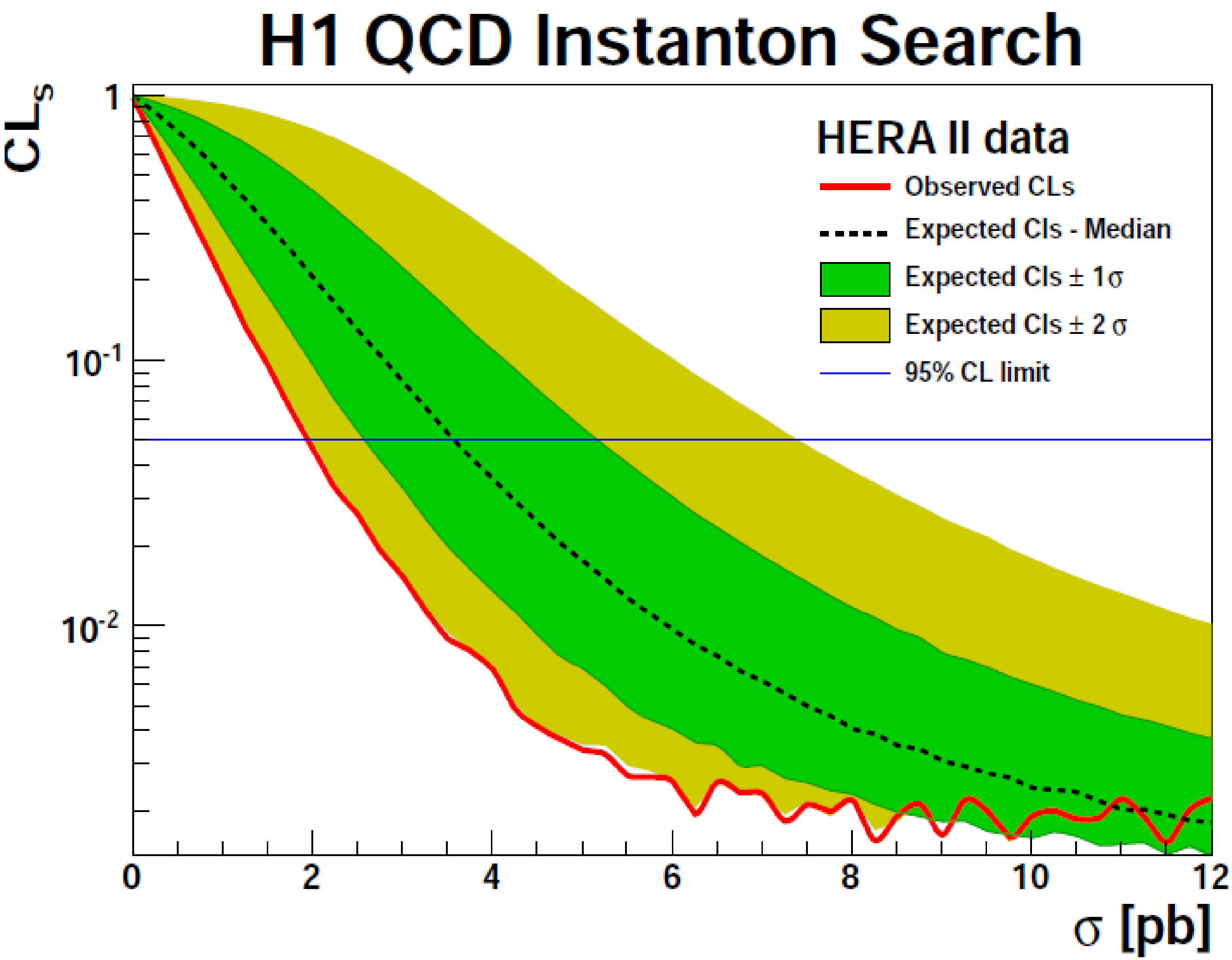
- CLs method
- Using full range discriminator
- Background:DJANGOH

- Experimental syst uncertainties
- Difference DJANGOH-RAPGAP as ± background model uncertainty
- 30% uncertainty of predicted signal cross section due to Λ_{QCD} uncertainty

Observed Upper Limit:
2 pb at 95% CL

Predicted cross section:

$$150 < Q^2 < 15000\ \mathrm{GeV}^2, \quad 0.2 < y < 0.7$$
$$Q'^2 > 109\ \mathrm{GeV}^2, \quad x' > 0.35$$
$$\sigma^{(I)} = 10\ \mathrm{pb}$$

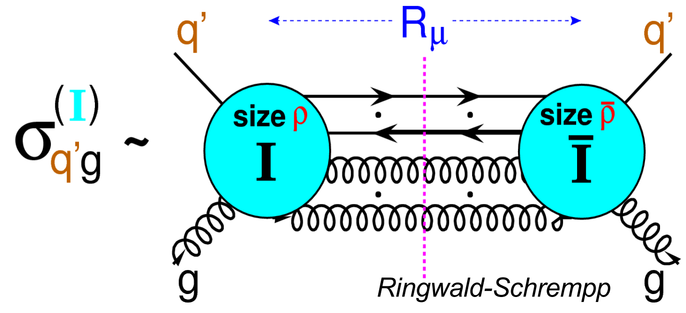


Exclusion limits on the plane Q'^2 vs x'

Calculation of instanton cross-section involves

I-size distribution (ρ) and

I-$\bar{\text{I}}$-distance distribution (R/ρ)



Key feature : there is a one-to-one relation between variables in momentum space (Q',x') and space variables (ρ,R)

Large Q' ↔ small ρ

Large x' ↔ large R/ρ

Limits:

- **contain additional meaning in terms of instantons size/distance**
- **allow to assess the effect of the steeply falling x' and Q' distributions**

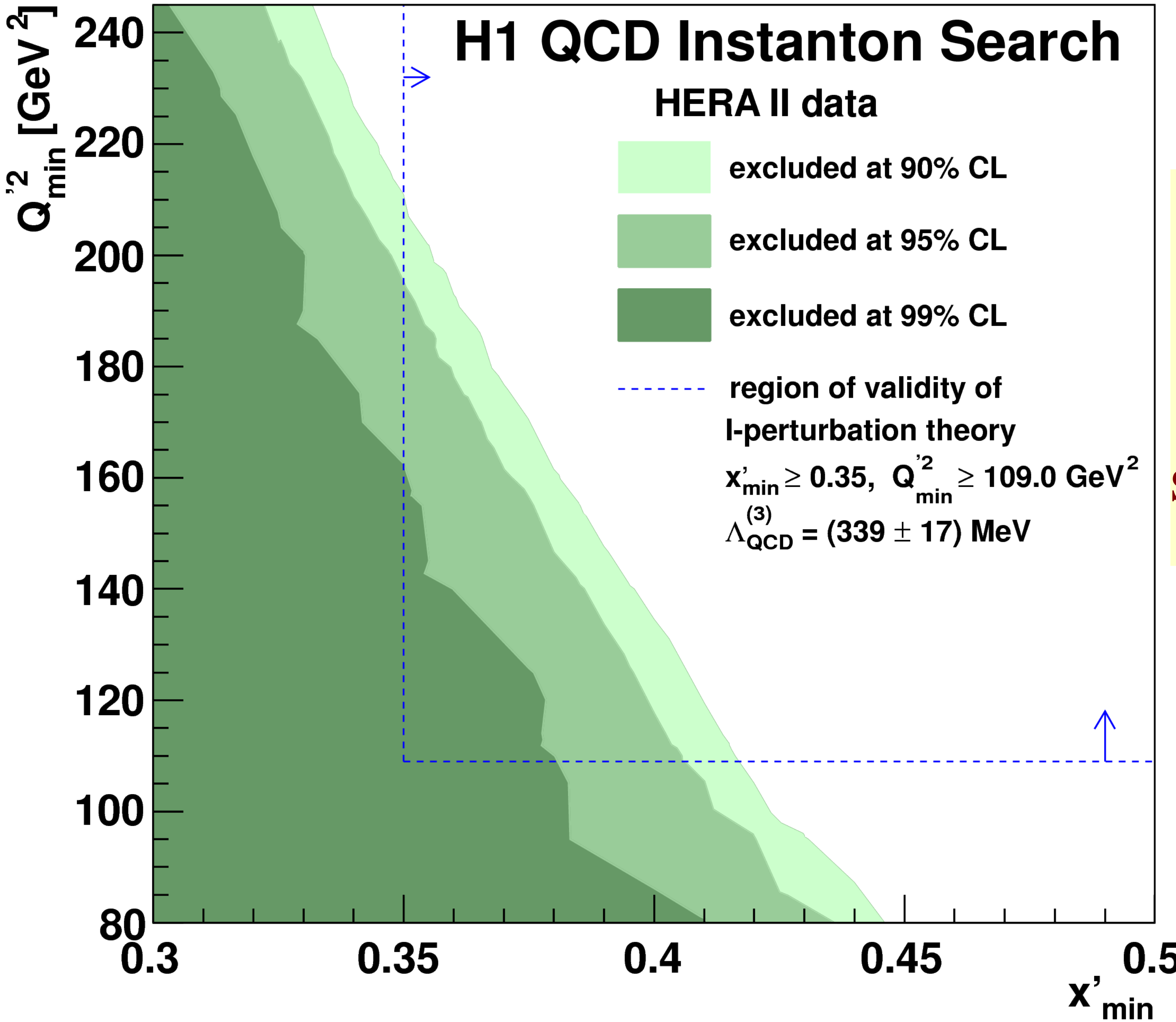
Region of validity of I-perturbation theory in (Q',x')

from

Confrontation with lattice results for QCD(nf=0):

$$\left.\begin{aligned} \varrho &< \varrho_{max} \approx 0.35\,\text{fm} \\ \frac{R}{\varrho} &> \left(\frac{R}{\varrho}\right)_{min} \approx 1.05 \end{aligned}\right\} \Rightarrow \left\{\begin{aligned} Q'^2 &> (30.8\,\Lambda_{\overline{MS}}^{n_f=3})^2 \approx 109\,\text{GeV}^2 \quad (\Lambda_{\overline{MS}}^{n_f=3} = 339 \pm 17\,\text{MeV}) \\ x' &> 0.35 \end{aligned}\right.$$

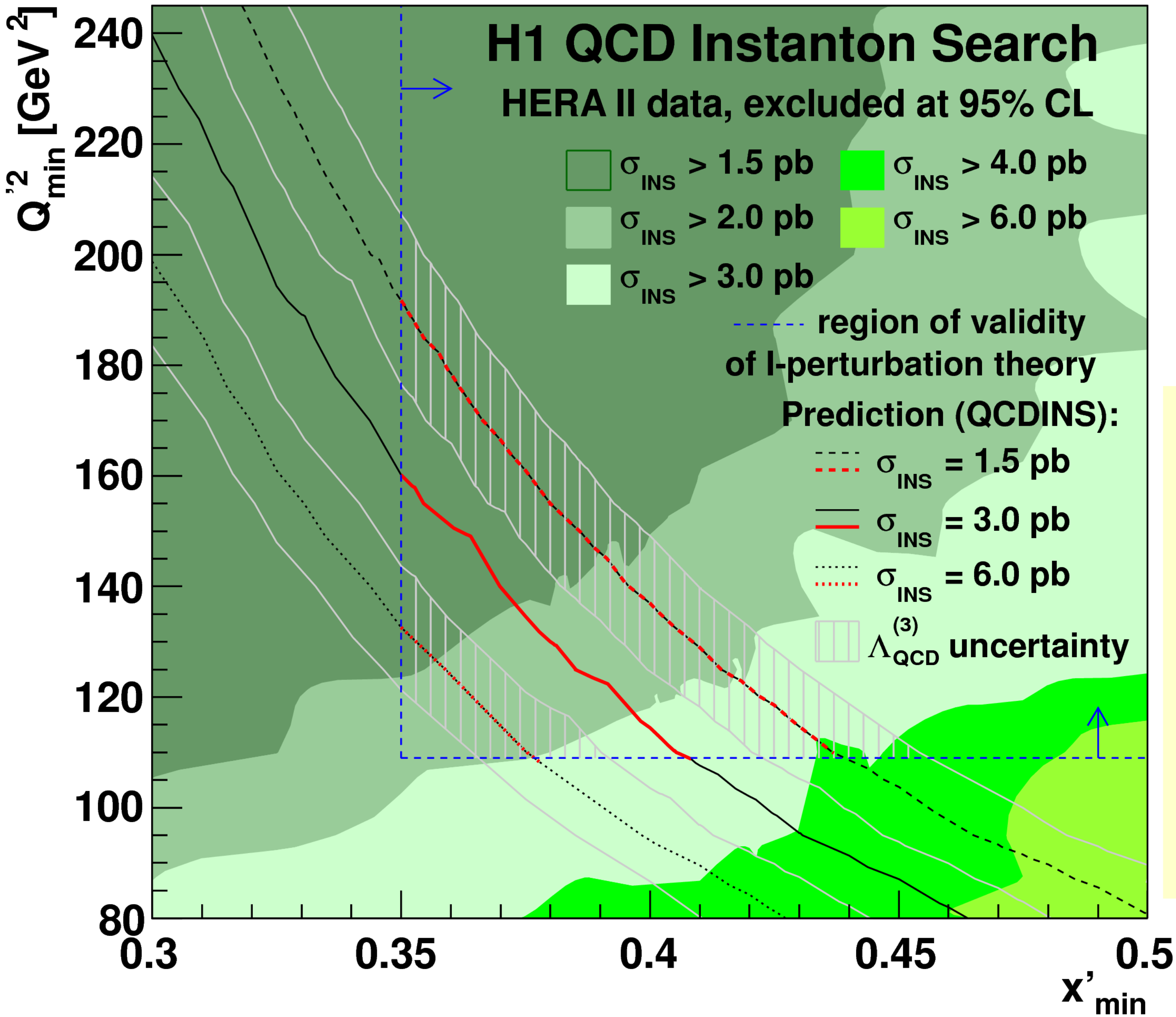
Exclusion Limits



Exclusion limits on Q'^2-x' plane as $Q'^2 > Q'^2_{min}$, $x' > x'_{min}$

Significant part is excluded

Upper limits on Instanton Production Cross Section at 95% CL



Upper limits on cross section 1.5 - 6 pb at 95%CL are set depending on kinematic domain

- Most strigent exclusion limits σ_{lim}~1.5 pb observed for large Q'^2_{min} and small x'_{min}
- For increasing x'_{min} limits become weaker

Summary

- The discovery of instantons would be the first evidence for topological fluctuations of a non-perturbative aspect of QCD

- H1 performed searches in high Q^2 regime for instanton-induced DIS processes predicted by A. Ringwald and F. Schrempp

- No evidence for QCD instanton induced processes is observed

- In the nominal kinematic region $x'>x'_{min}=0.35$ and $Q'^2>Q'^2_{min}=113$ GeV^2 an upper limit of 2 pb on the instanton cross section at 95 % CL, and the predicted cross section 10 pb is excluded

- Limits are also set in the kinematic plane depending on x'_{min} and Q'^2_{min}. They may be used to assess the compatibility of various theoretical assumptions

- Instanton exclusion limits are improved by an order of magnitude and are challenging theory prediction for the first time