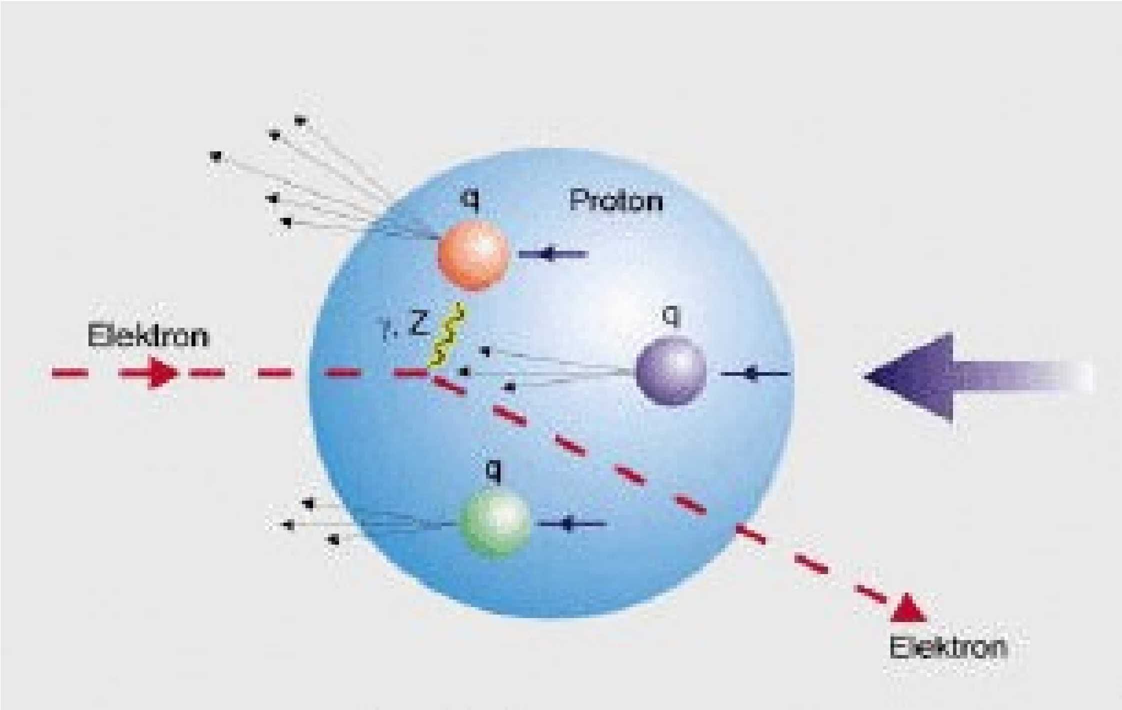
4th Particle Physics Workshop

National Center for Physics, Islamabad

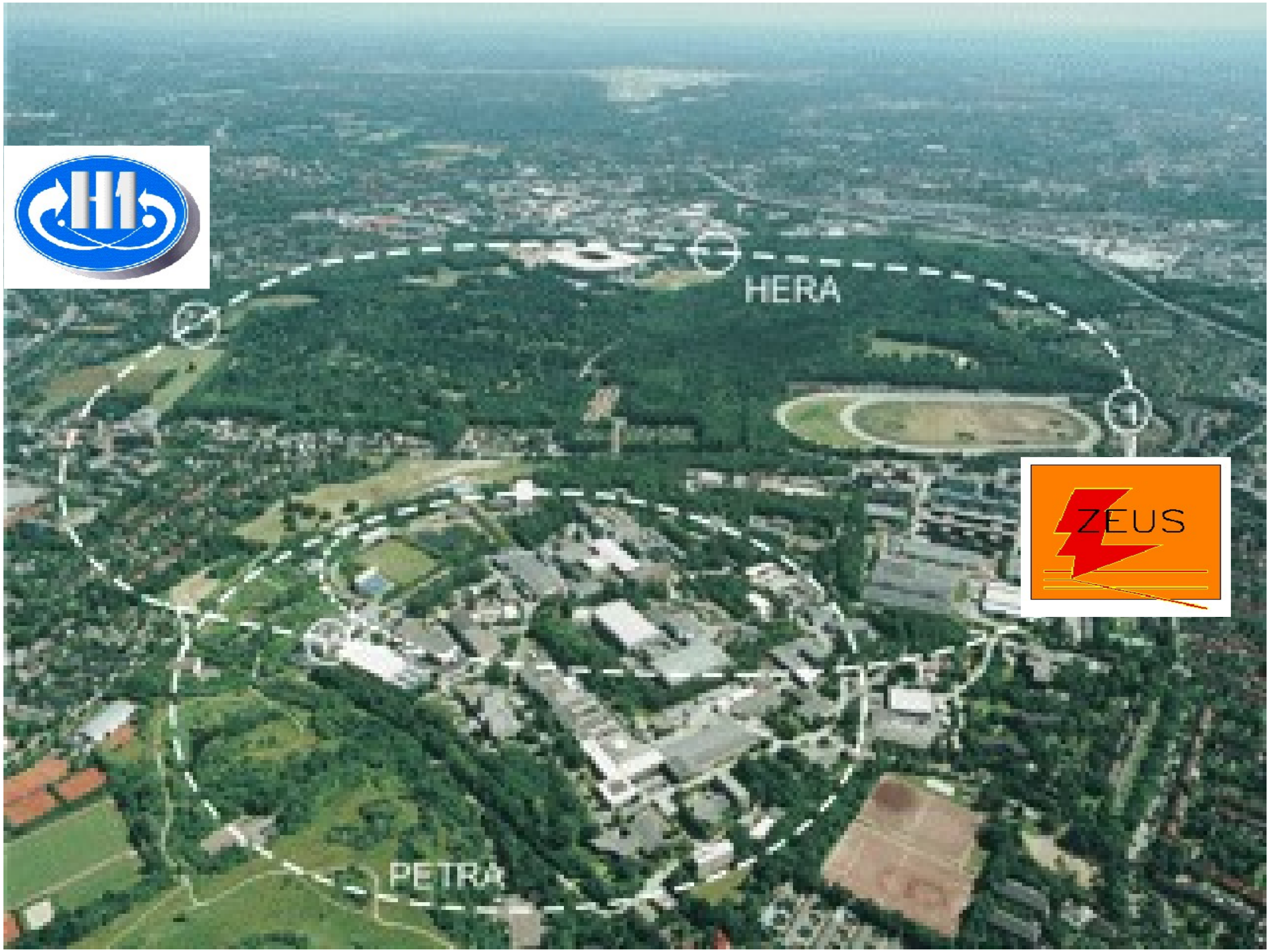
Proton Structure and QCD tests at HERA

Jan Olsson, DESY

Part 1



ep collider HERA at DESY in Hamburg, Germany



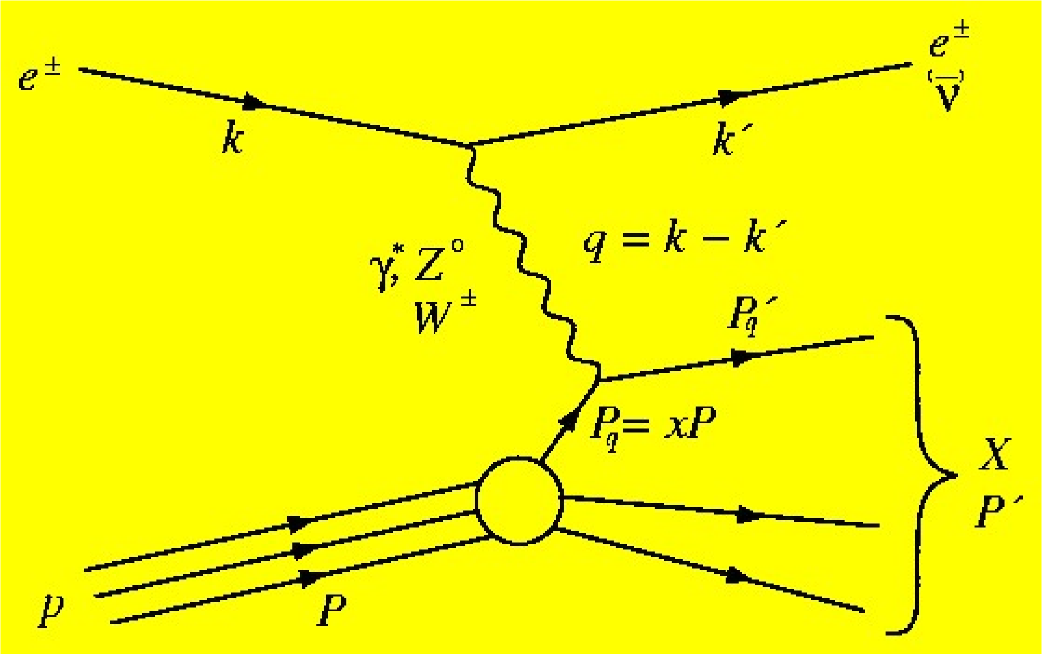
E_e = 27.6 GeV

E_p = 920 GeV

318 GeV CM energy

corresponds to
54 TeV beam energy
for a fixed target!

Asymmetric accelerator, superconducting technology, 6.3 km circumference
Operates since 1992,
H1 and ZEUS colliding beam experiments, fixed target experiment HERMES



HERA Kinematics

$$Q^2 = -q^2 = -(k - k')^2$$ Boson virtuality, resolution scale

$$x = \frac{Q^2}{2Pq}$$ Fractional momentum of struck quark

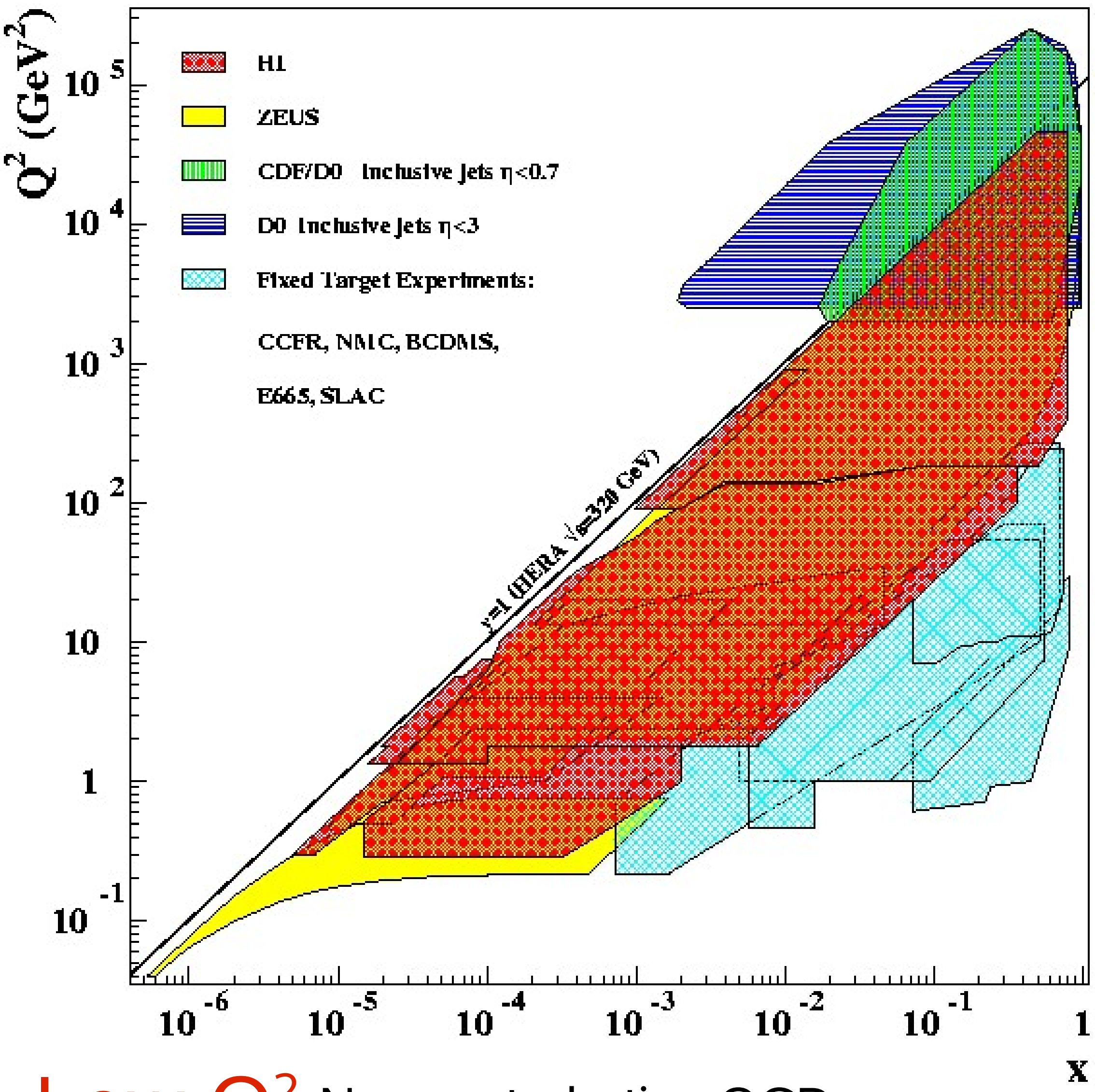
Bjorken scaling variable

$$y = \frac{p \cdot q}{p \cdot k}$$ Inelasticity

$$s = (p + k)^2$$ CM energy of the ep system (squared)

$$W^2 = (q + p)^2$$ Boson-proton CM energy, “hadronic mass”

$$Q^2 \simeq xys$$ 2 independent variables



Low Q^2
Low x

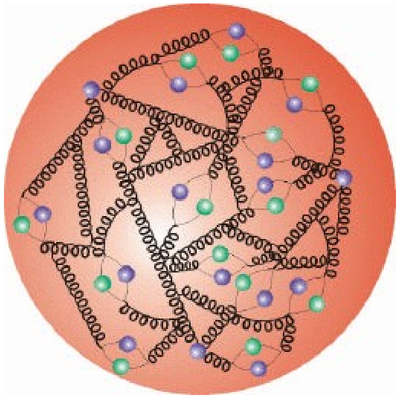
Non-perturbative QCD
Transition to “soft” physics
Saturation search
Test validity of evolution schemes

High Q^2, high x

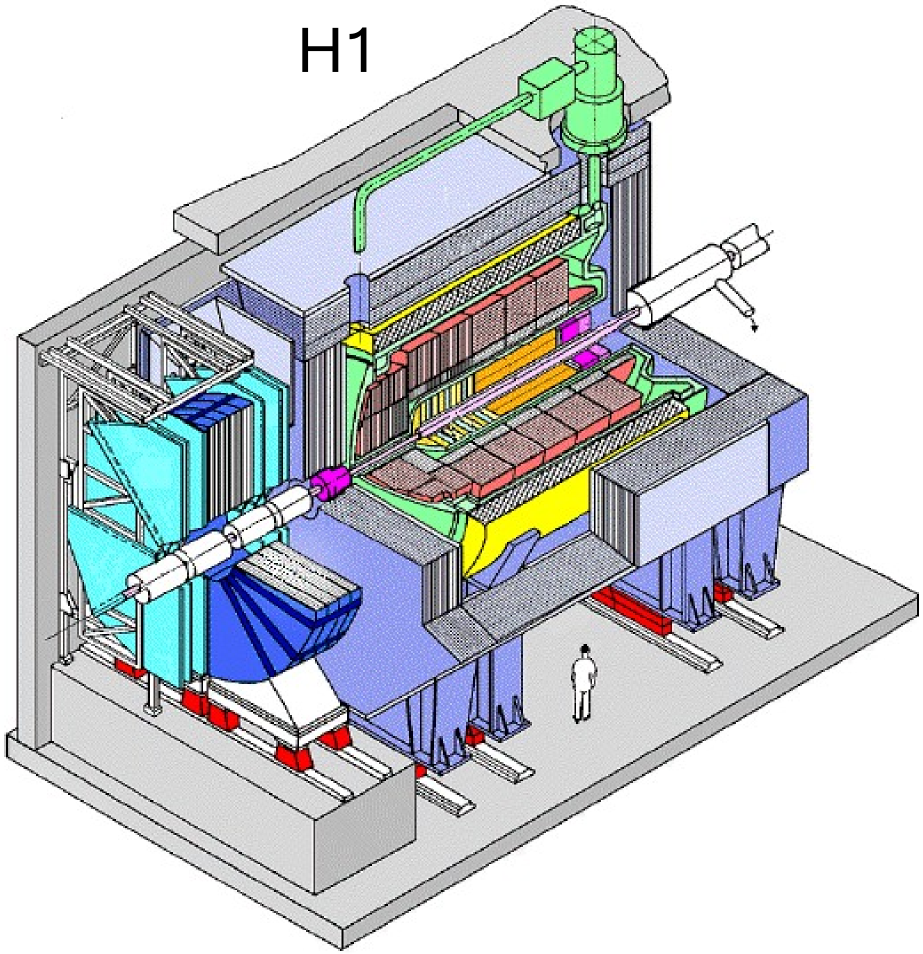
Perturbative QCD
Electroweak effects
Overlap in x
with fixed target experiments

HERA can test QCD over wide range of Q^2 and x

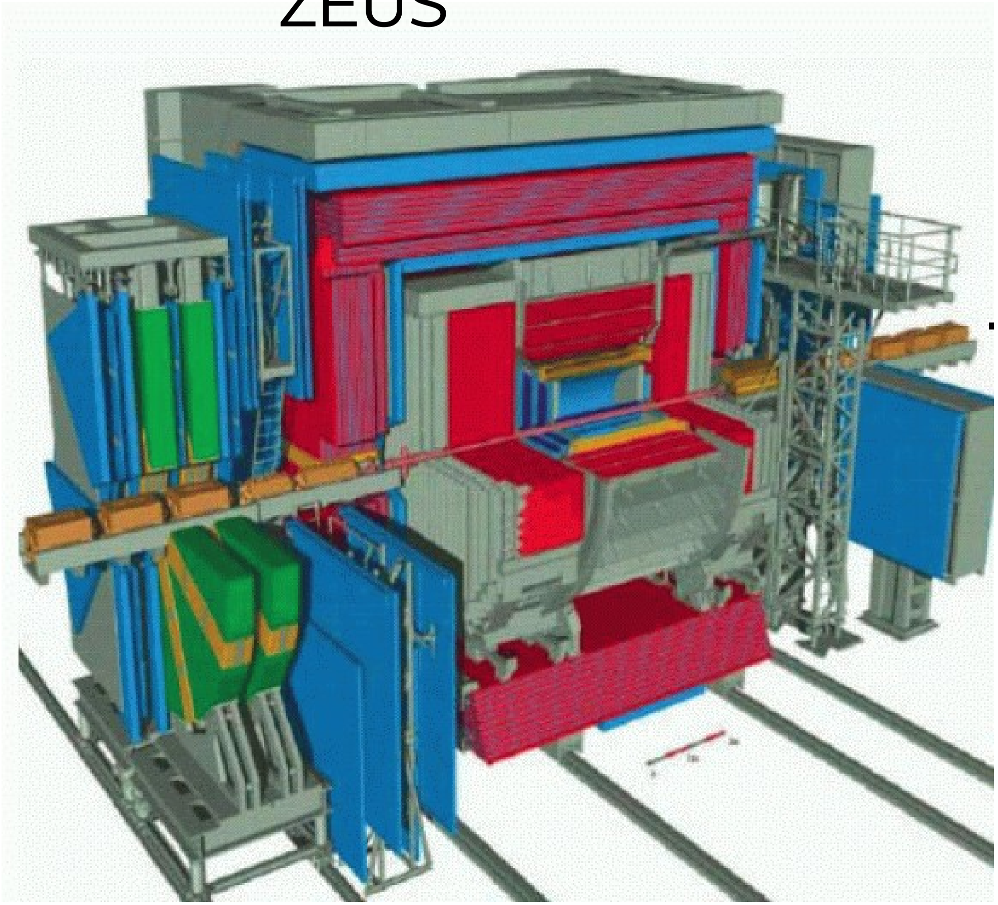
Explore proton structure !



H1



ZEUS



Central, backward and forward tracking

Liquid Argon (H1) and Compensating Uranium (ZEUS) calorimeters

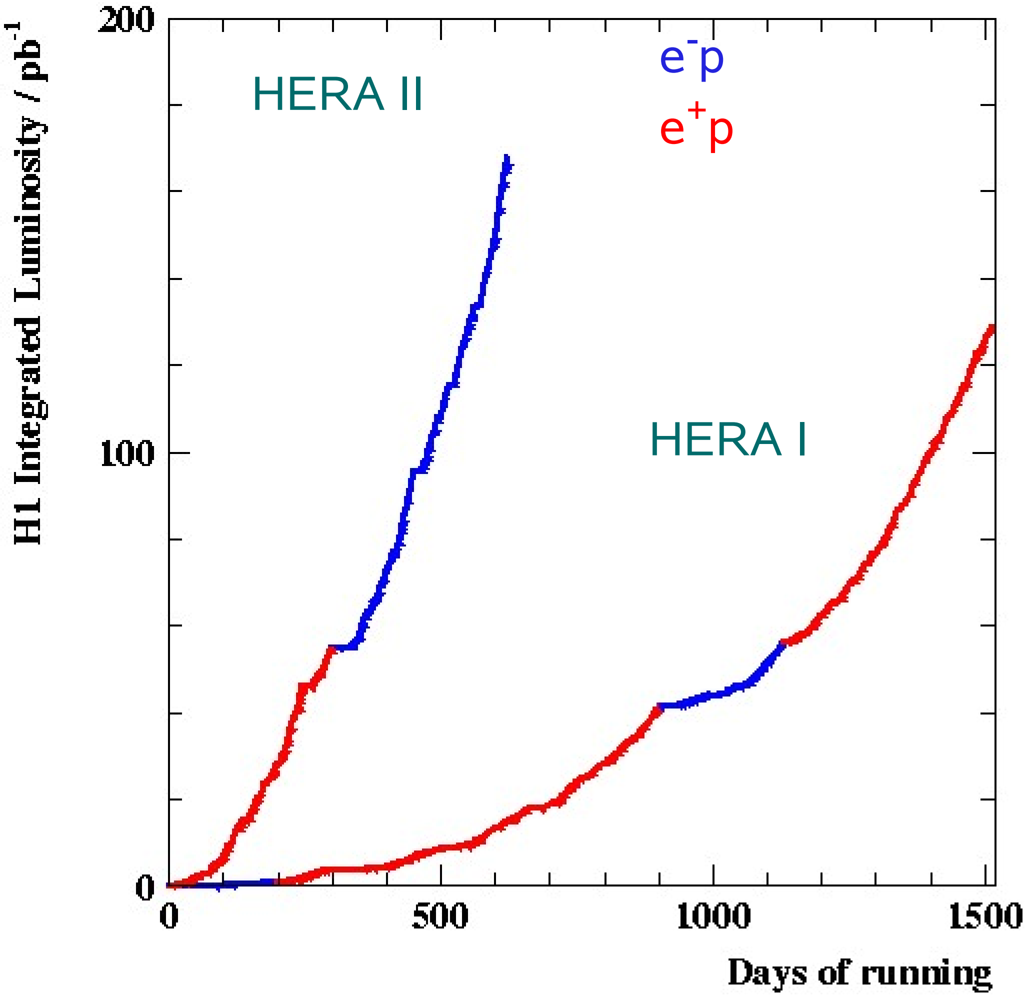
Vertex detectors

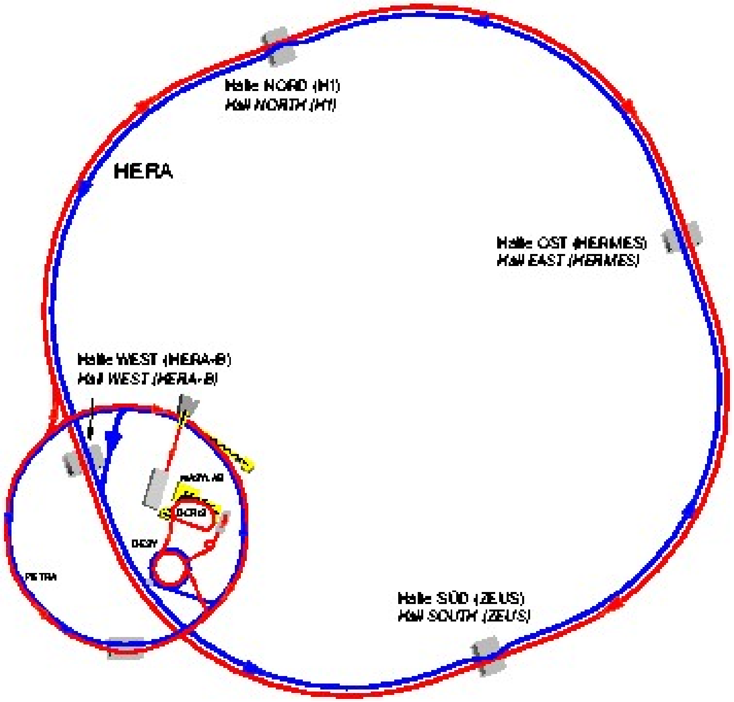
Solenoidal and Toroidal fields, Forward and Central Muon detectors

Forward detectors: Roman pots, Neutron calorimeters

Electron and Photon tagging detectors

Integrated Luminosity





HERA I data:
~120 pb^{-1} per experiment

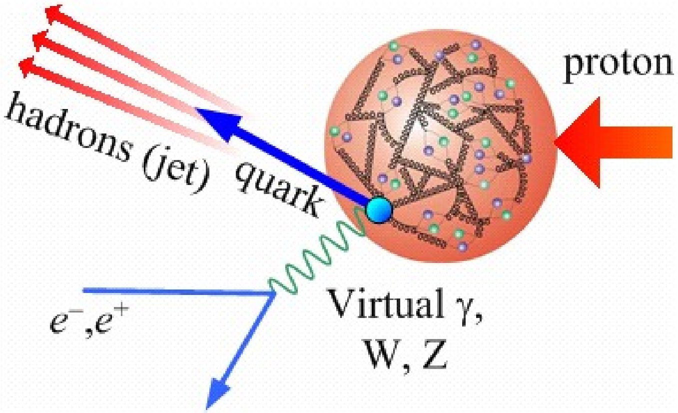
HERA II data (by end of 2005):
~170 pb^{-1} per experiment

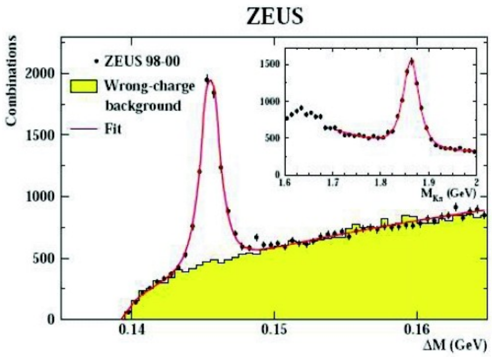
HERA II Upgrade 2001-02:
- Spin rotators for H1 and ZEUS
- Luminosity increase

HERA operation ends 7/2007

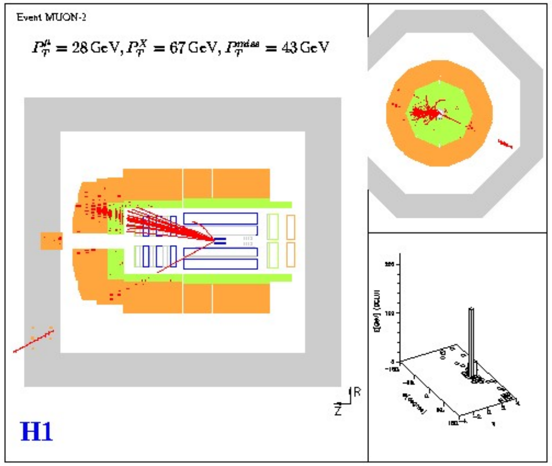
HERA Physics

- Neutral and Charged Current DIS
- Proton Structure
- Jet production and QCD studies
- Heavy Quark (c and b) production
- Hadronic Final State
- Spectroscopy
- Photoproduction
  - Photon Structure
- Diffraction
  - Exclusive Final States
  - Leading Baryon production
- Search for exotics, BSM
- ……………….

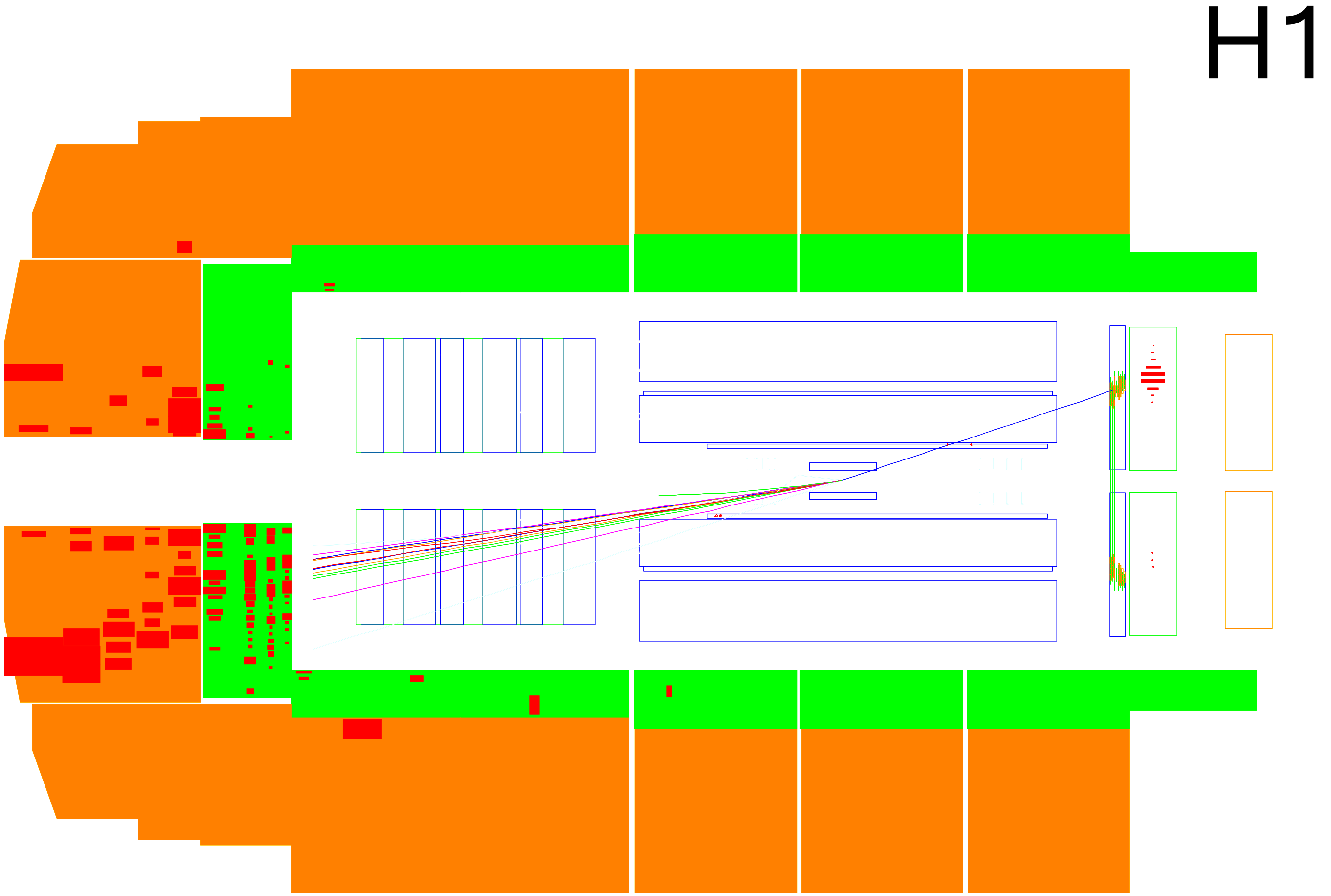




$e^+p \rightarrow \mu^+X$

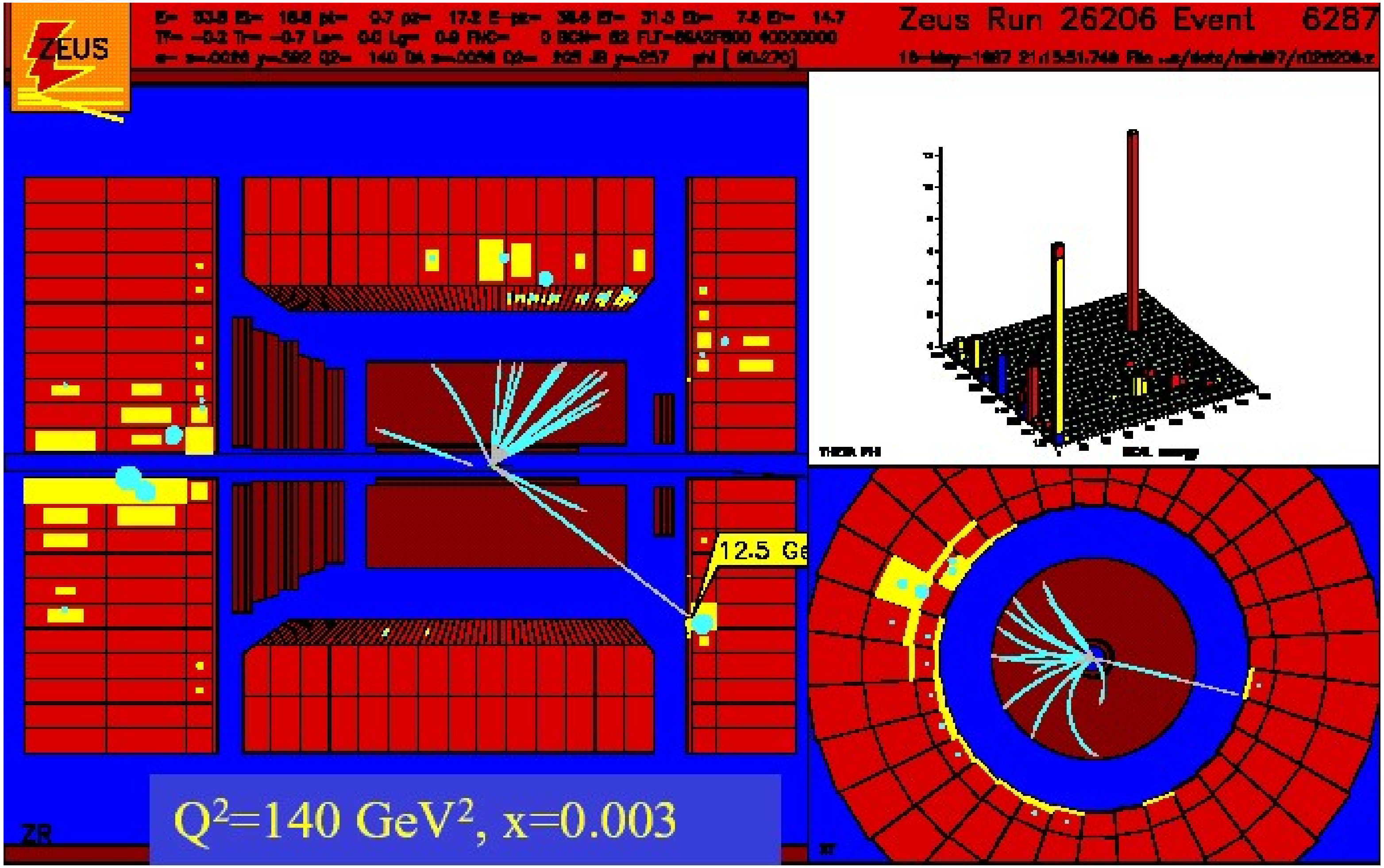


Neutral Current event, medium Q^2



Kinematics determined from measured electron, as well as from the hadronic system (energies and angles)

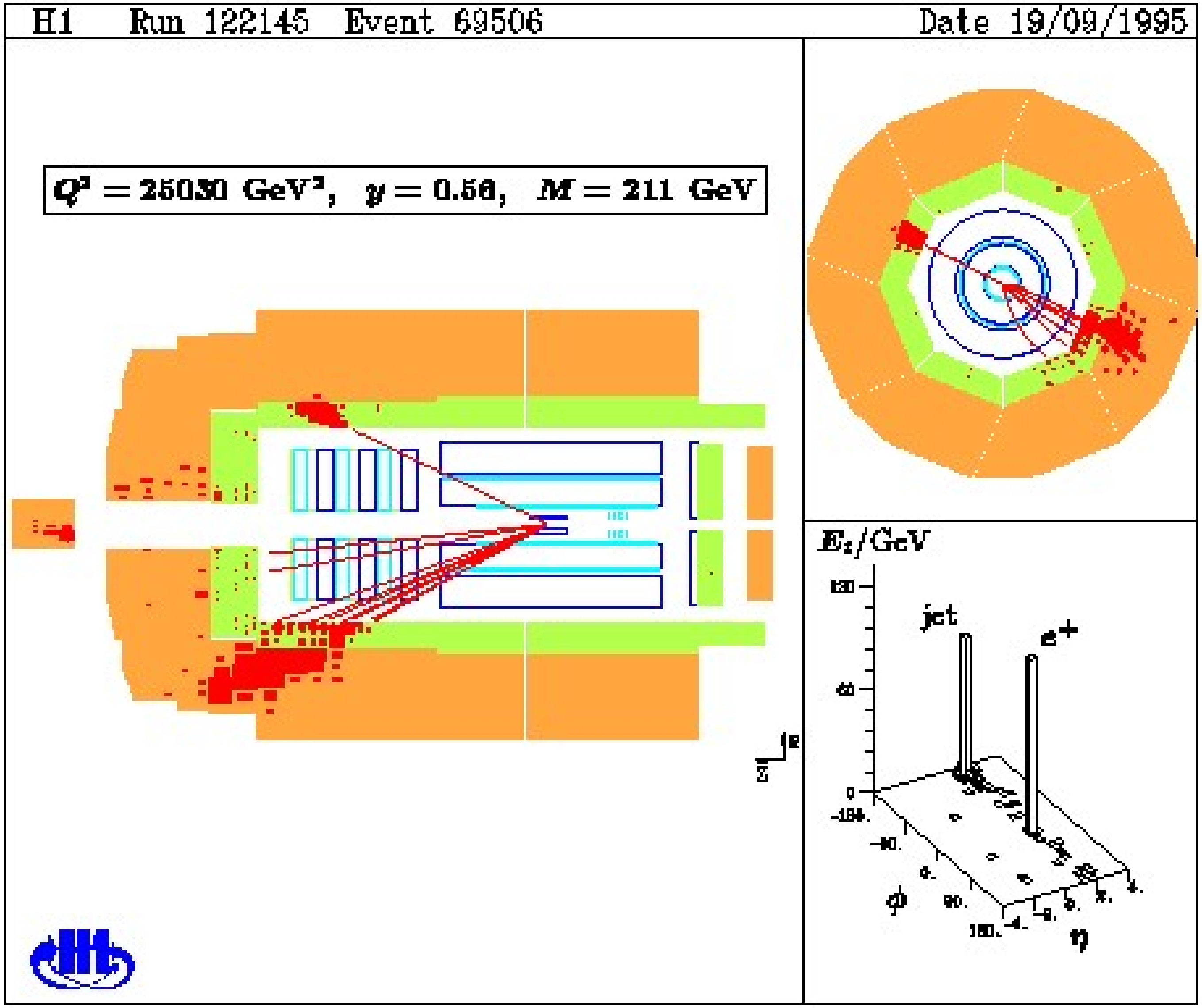
Neutral Current event, medium Q^2



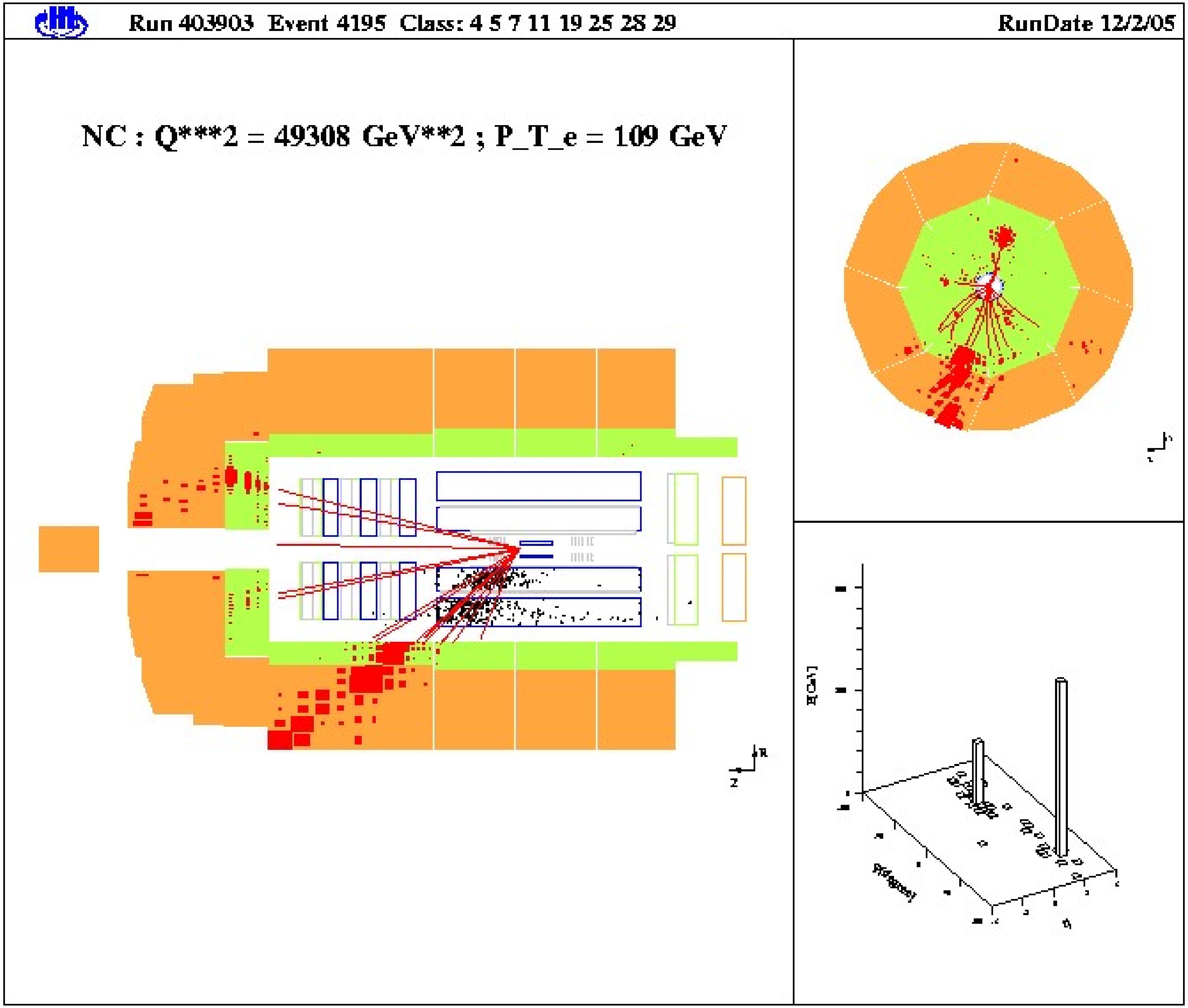
$Q^2 = 140\ \mathrm{GeV}^2$, $x = 0.003$

Neutral Current event, high Q^2

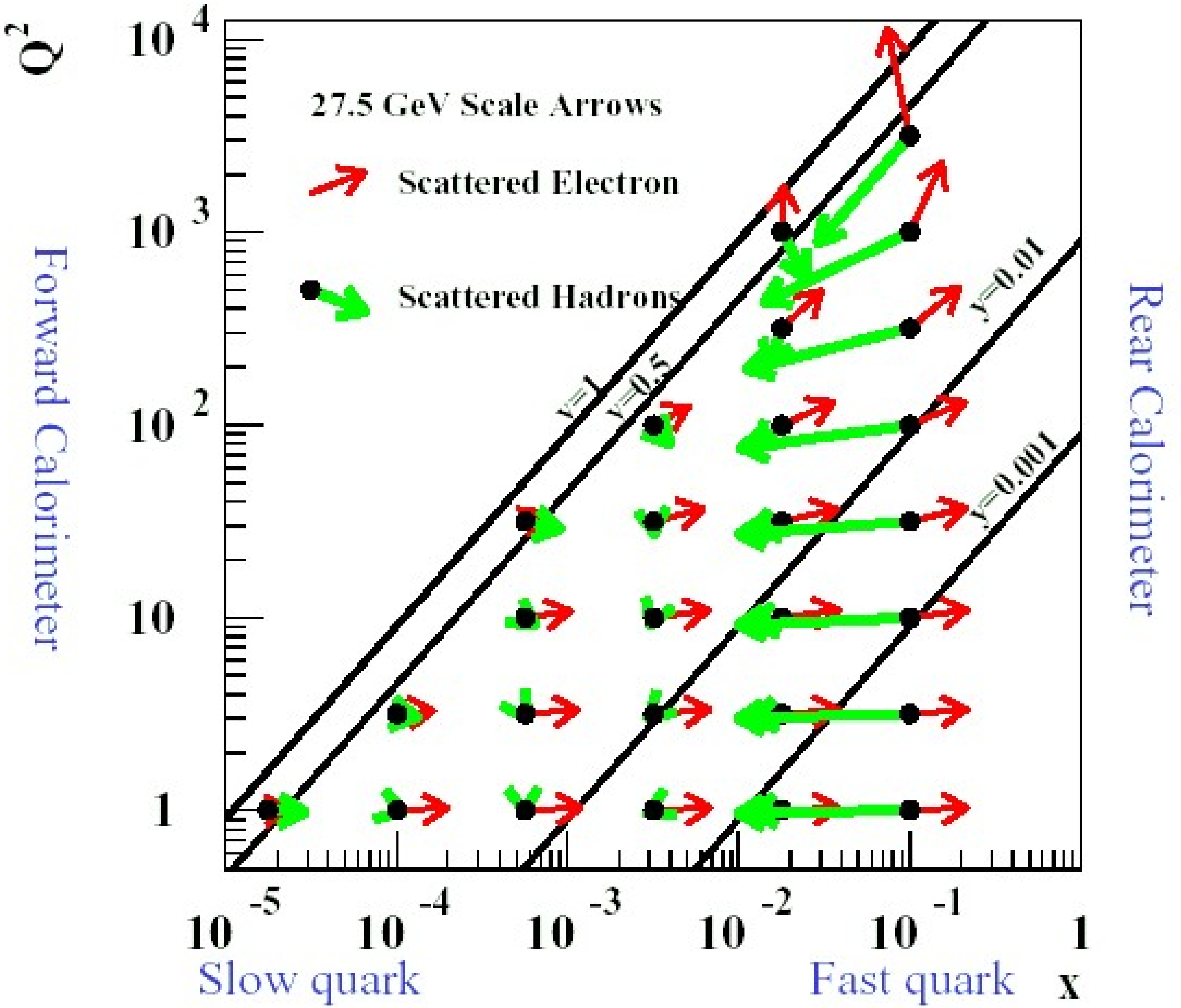
Candidate from NC sample



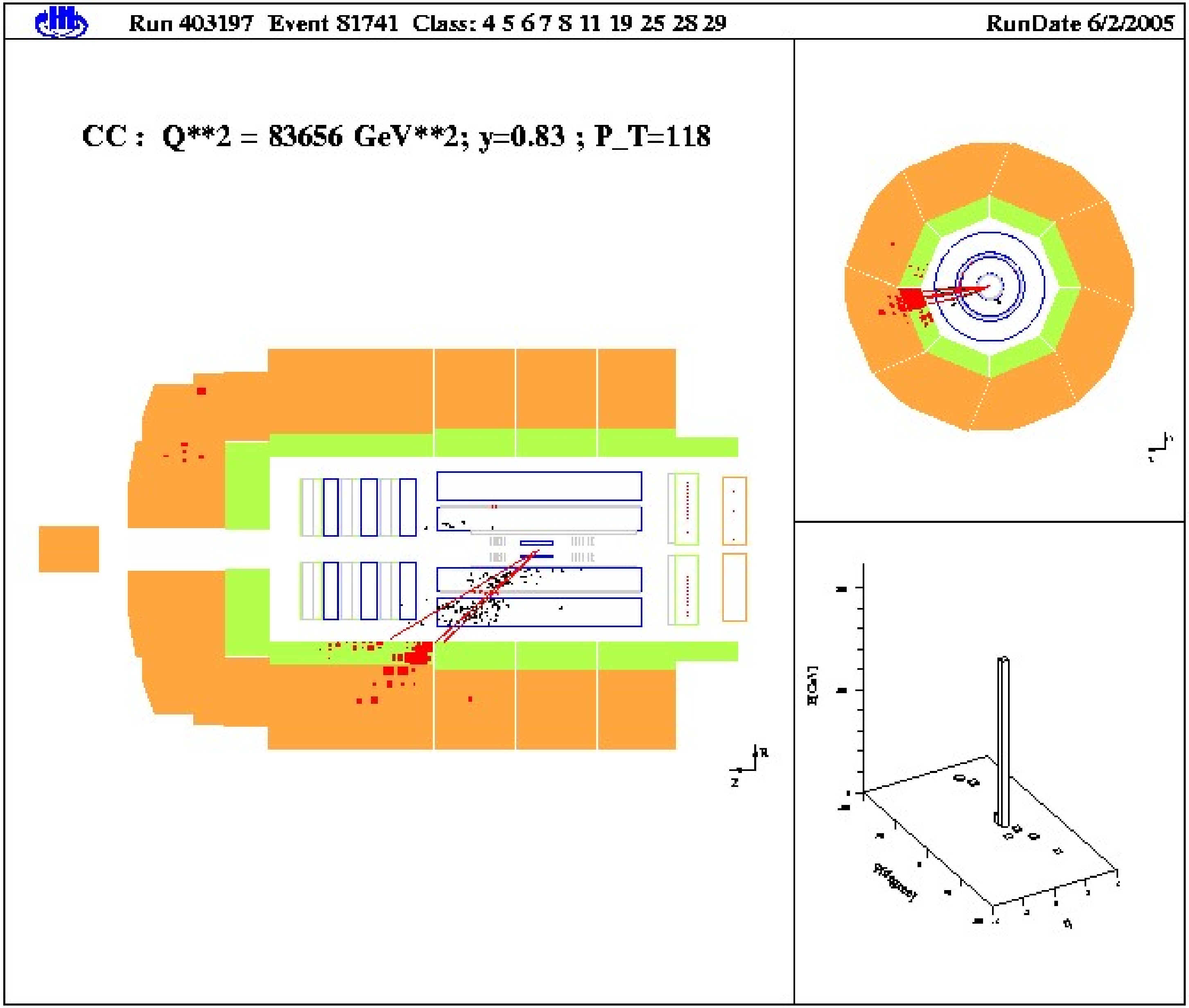
Neutral Current event, high Q^2



A new look at the kinematic plane:



Charged Current event



Kinematics here determined from hadronic system alone, using energy and angle

No redundancy

Neutral Current Cross Section

$$\frac{d^2\sigma^{\pm}_{NC}}{dx\, dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3 - y^2\tilde{F}_L\right]$$

$$Y_\pm \equiv 1 \pm (1-y)^2$$

$$\tilde{F}_2 \equiv F_2 - v_e \frac{\kappa Q^2}{(Q^2+M_Z^2)} F_2^{\gamma Z} + (v_e^2 + a_e^2)\left(\frac{\kappa Q^2}{Q^2+M_Z^2}\right)^2 F_2^Z$$

$$x\tilde{F}_3 \equiv -a_e \frac{\kappa Q^2}{(Q^2+M_Z^2)} xF_3^{\gamma Z} + (2v_e a_e)\left(\frac{\kappa Q^2}{Q^2+M_Z^2}\right)^2 xF_3^Z$$

$$\kappa^{-1} = 4\frac{M_W^2}{M_Z^2}\left(1 - \frac{M_W^2}{M_Z^2}\right)$$

$$F_2 = x\sum_q e_q^2\{q+\overline{q}\}$$

$$F_2^{\gamma Z} = x\sum_q 2e_q v_q\{q+\overline{q}\}$$

$$F_2^Z = x\sum_q (v_q^2 + a_q^2)\{q+\overline{q}\}$$

e_q	quark charges
v_q, a_q	quark couplings to Z0
$q(x,Q^2)$	quark momentum distributions

$q - \bar{q}$

`==> access to`
`    valence quark`
`    distributions`

$$xF_3^{\gamma Z} = 2x\sum_q e_q a_q\{q-\overline{q}\} = 2x\sum_{q=u,d} e_q a_q\, q_v$$

$$xF_3^{Z} = 2x\sum_q v_q a_q\{q-\overline{q}\} = 2x\sum_{q=u,d} v_q a_q\, q_v$$

Charged Current Cross Section

$$\frac{\mathrm{d}^2\sigma^{\pm}_{CC}}{\mathrm{d}x\,\mathrm{d}Q^2} = \frac{G_F^2}{2\pi x}\left[\frac{M_W^2}{Q^2+M_W^2}\right]^2 \frac{1}{2}\left(Y_+ W_2^{\pm} \mp Y_- xW_3^{\pm} - y^2 W_L^{\pm}\right)$$

$$\begin{aligned} W_2^+ &= x(\overline{U} + D) \\ W_2^- &= x(U + \overline{D}) \\ xW_3^+ &= x(D - \overline{U}) \\ xW_3^- &= x(U - \overline{D}) \end{aligned}$$

$$\begin{aligned} xU &= x(u + c) \\ x\overline{U} &= x(\overline{u} + \overline{c}) \\ xD &= x(d + s) \\ x\overline{D} &= x(\overline{d} + \overline{s}) \end{aligned}$$

For convenience: Reduced cross sections:

$$\tilde{\sigma}_{NC}(x,Q^2) = \frac{1}{Y_+}\,\frac{Q^4\,x}{2\pi\alpha^2}\,\frac{\mathrm{d}^2\sigma_{NC}}{\mathrm{d}x\mathrm{d}Q^2} = F_2(1+\Delta_{F_2}+\Delta_{F_3}+\Delta_{F_L})$$

$$\tilde{\sigma}_{CC}(x,Q^2) = \frac{2\pi x}{G_F^2}\left[\frac{M_W^2+Q^2}{M_W^2}\right]^2 \frac{\mathrm{d}^2\sigma_{CC}}{\mathrm{d}x\mathrm{d}Q^2}$$

(sometimes also called σ_r)

Structure Functions: Cross sections, where the kinematic factors have been divided out

The Neutral Current Cross section

Reduced cross section (NC)

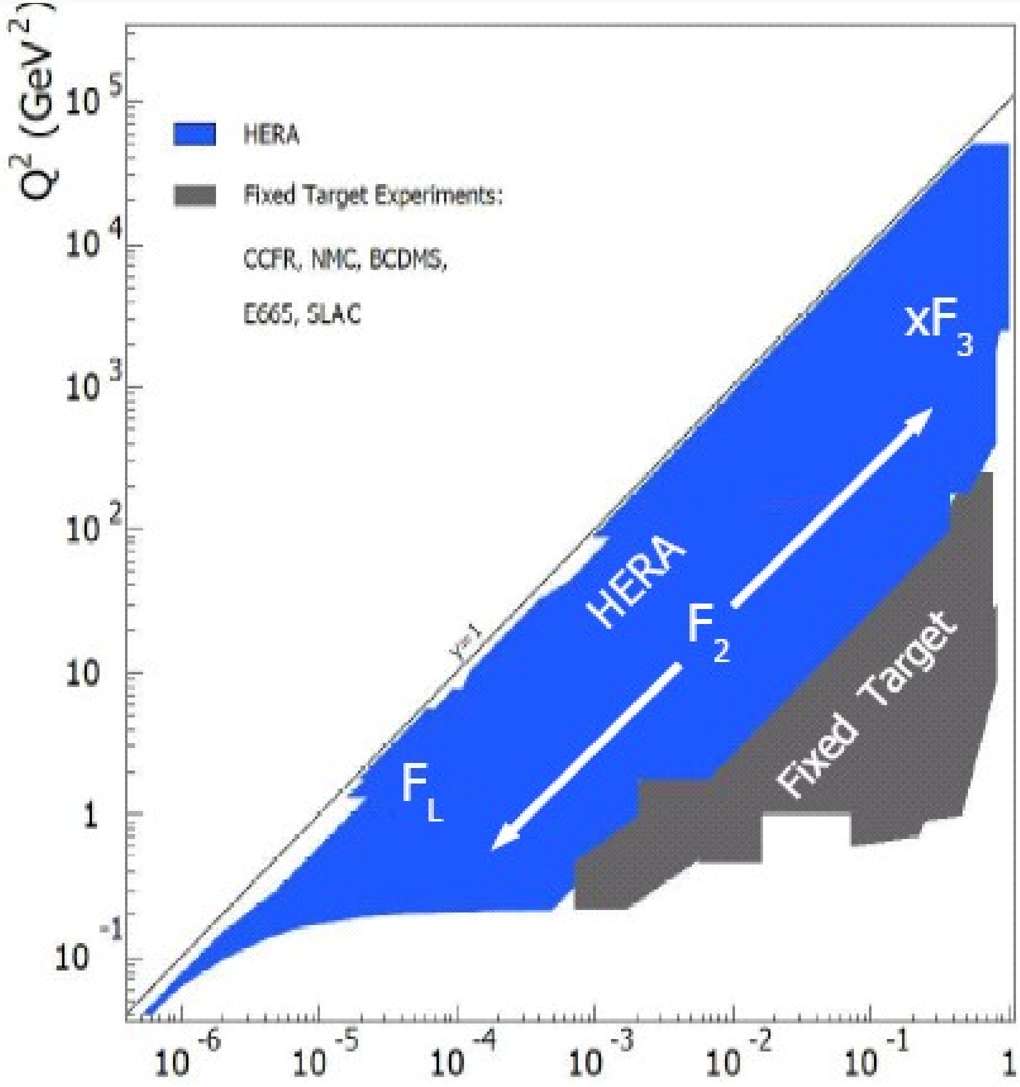
$$\tilde{\sigma}_{NC}(x,Q^2) \equiv \frac{1}{Y_+}\;\frac{Q^4\;\;x}{2\pi\alpha^2}\;\frac{\mathrm{d}^2\sigma_{NC}}{\mathrm{d}x\mathrm{d}Q^2} = F_2(1+\Delta_{F_2}+\Delta_{F_3}+\Delta_{F_L})$$

HERA extends the range in Q^2 by factor 100, compared with the fixed target experiments

Maximum Q^2 = 100000 GeV^2

Resolution power of 10^{-18}m

HERA gives the first look at proton structure at low x!



The $x\tilde{F}_3$ Structure Function

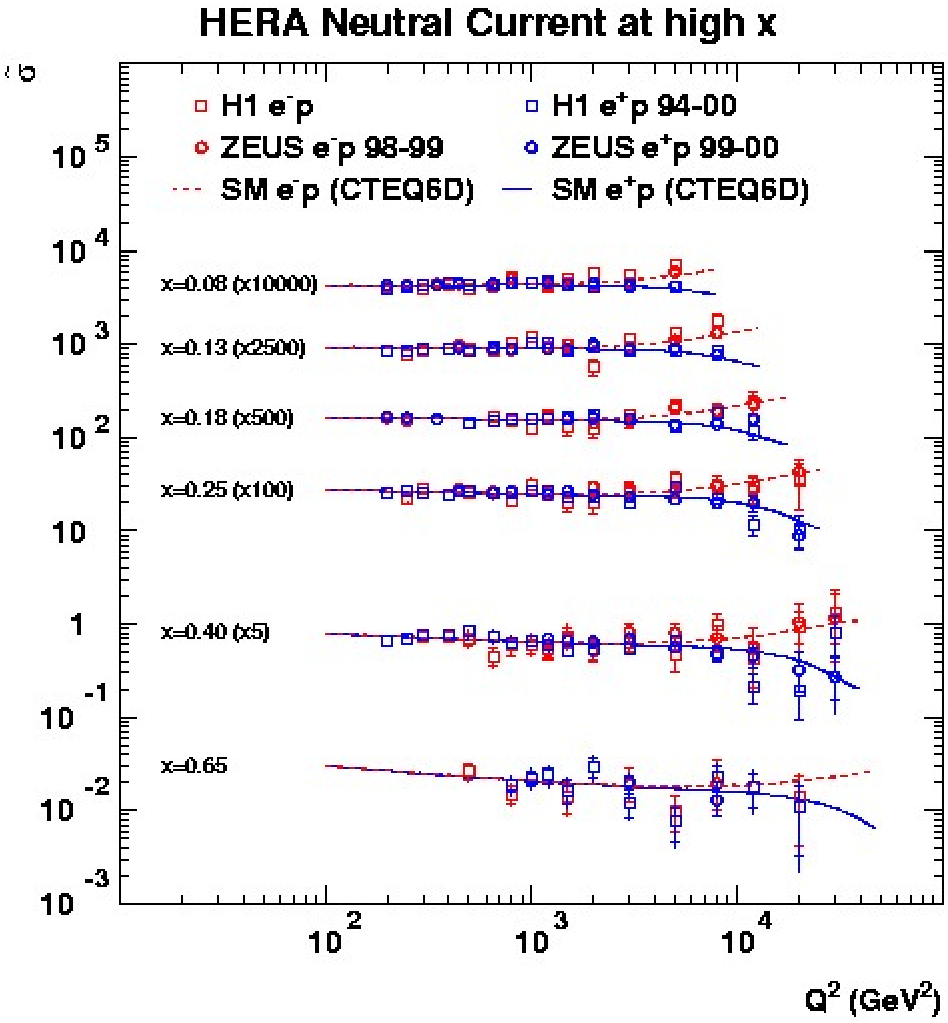
The contribution from $x\tilde{F}_3$ can be obtained by subtraction of e⁻p and e⁺p NC cross sections, at highest Q^2

$$x\tilde{F}_3 = \frac{1}{2Y_-}\left[\tilde{\sigma}^-_{NC} - \tilde{\sigma}^+_{NC}\right]$$

Pure Z^0 exchange neglected☆

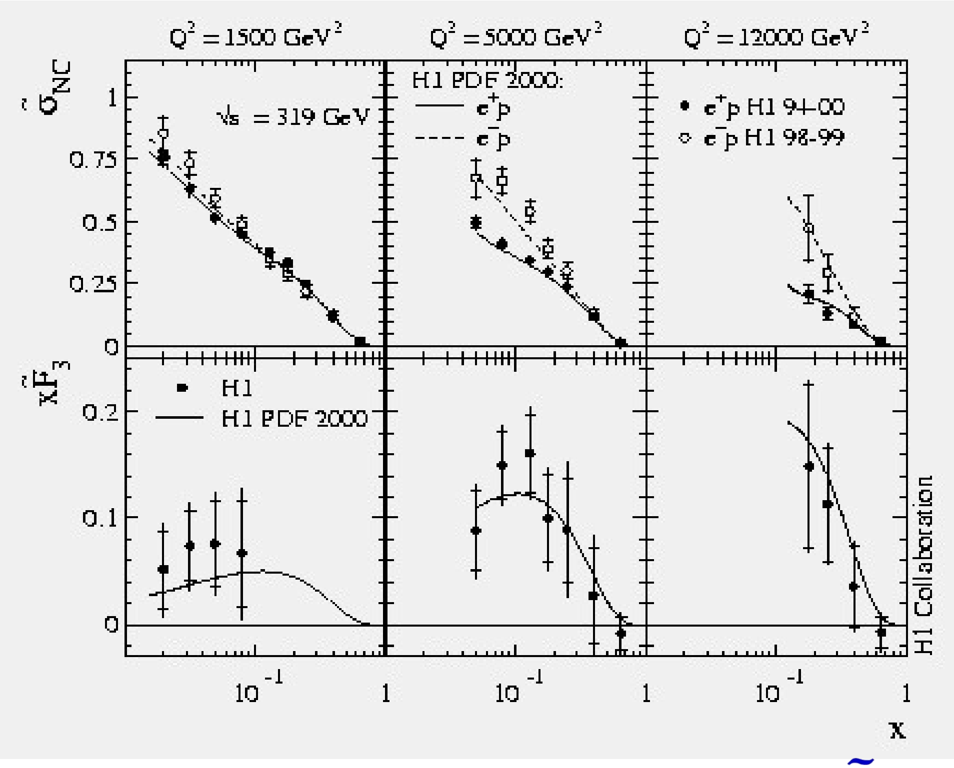
==> $$xF_3^{\gamma Z} \equiv xG_3$$

Reduced Cross Section



☆ $$x\tilde{F}_3 \equiv -\, a_e \frac{\kappa Q^2}{(Q^2+M_Z^2)} xF_3^{\gamma Z} + (2v_e a_e)\left(\frac{\kappa Q^2}{Q^2+M_Z^2}\right)^2 xF_3^Z$$

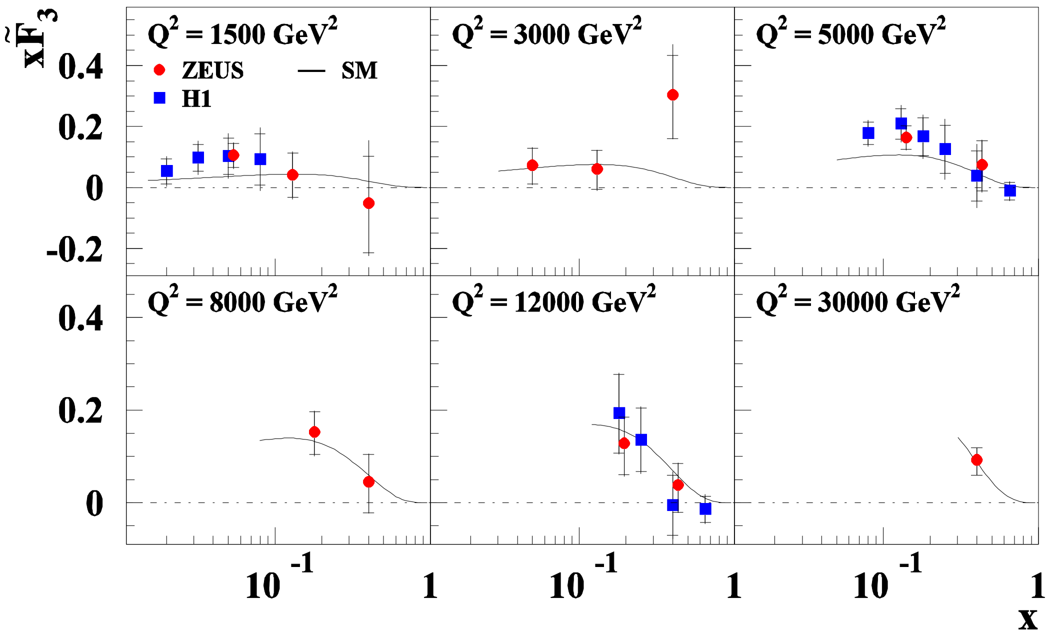
The $x\tilde{F}_3$ Structure Function



The dominant contribution to $x\tilde{F}_3$ comes from the interference term, since the pure Z-exchange term is suppressed by the small v_e.

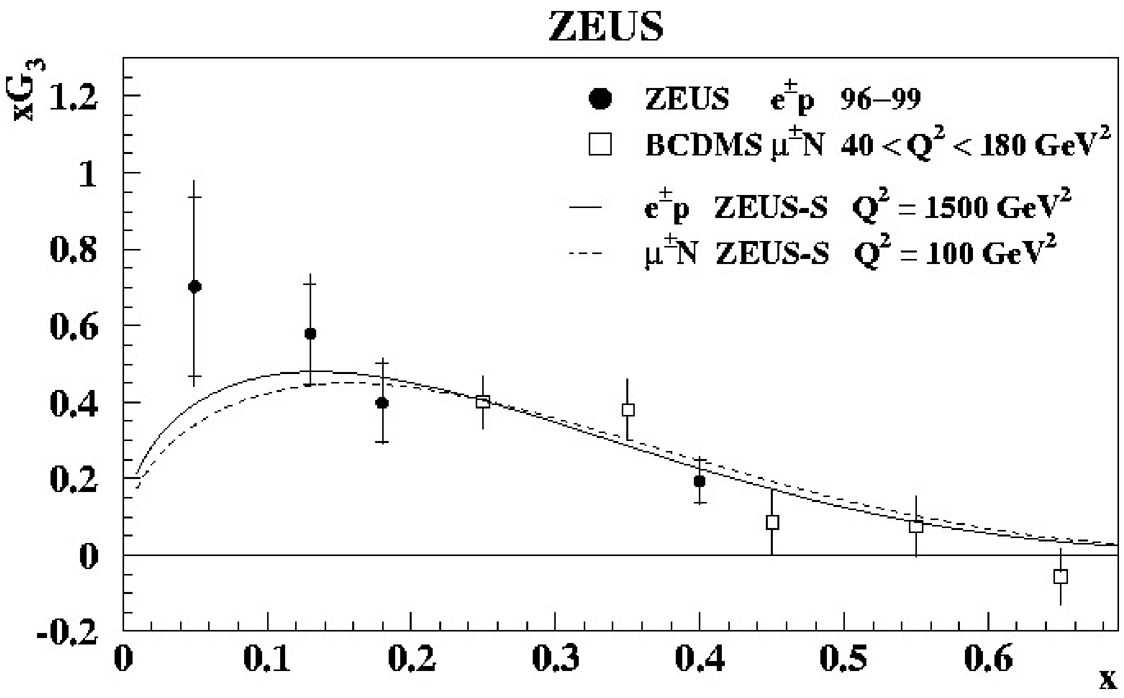
The interference term has only little dependence on Q²

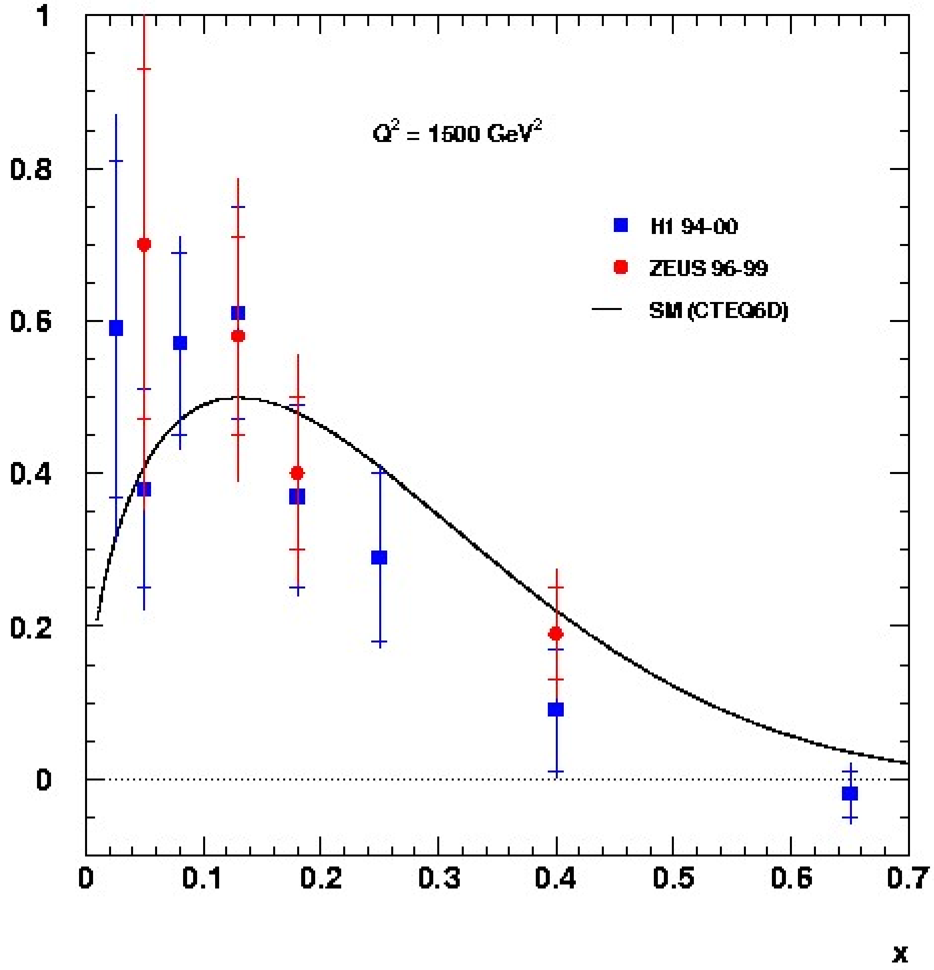
==> take average over Q²



The NLO QCD fit describes the data; Valence partons in this region constrained by the NC and CC cross sections, rather than by the e⁺ and e⁻ NC cross section difference.

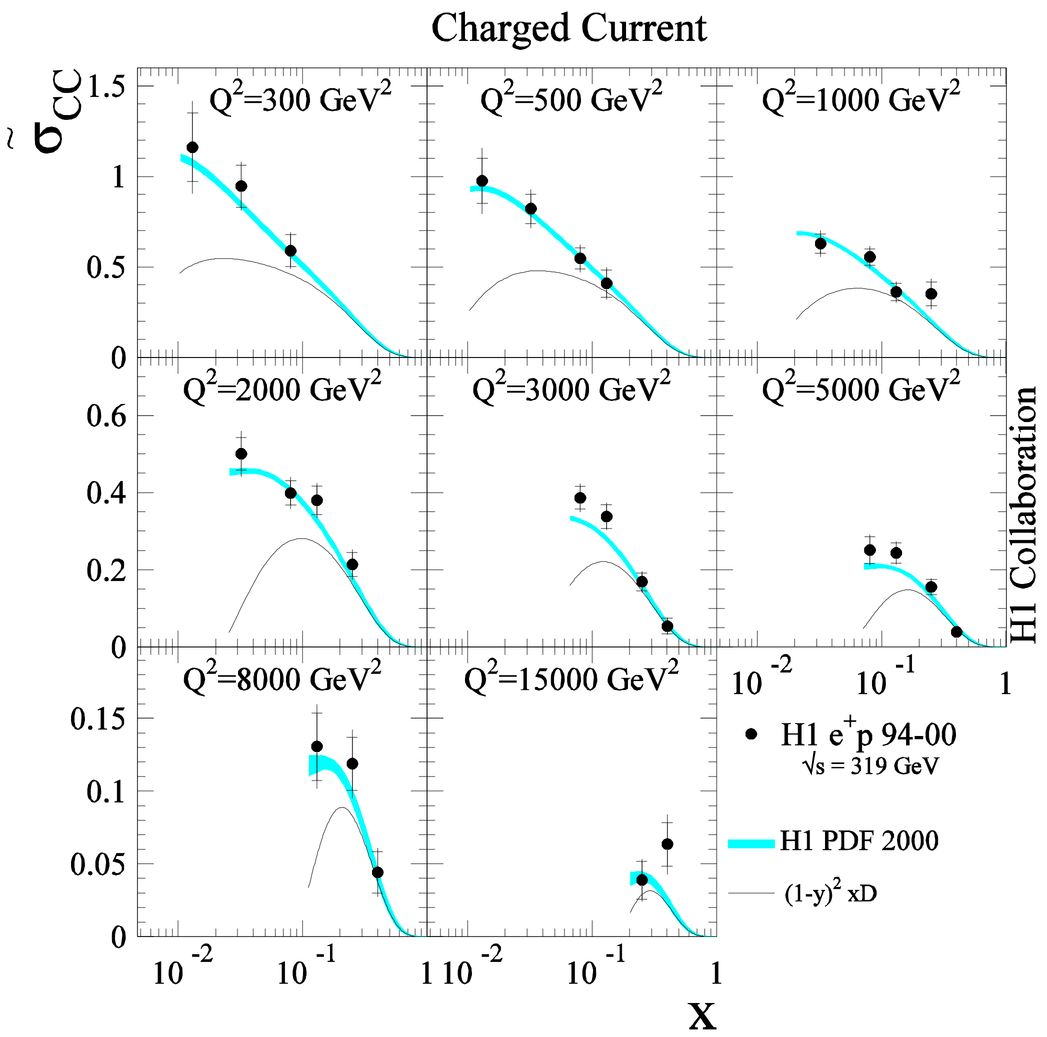
The $x\tilde{F}_3$ Structure Function

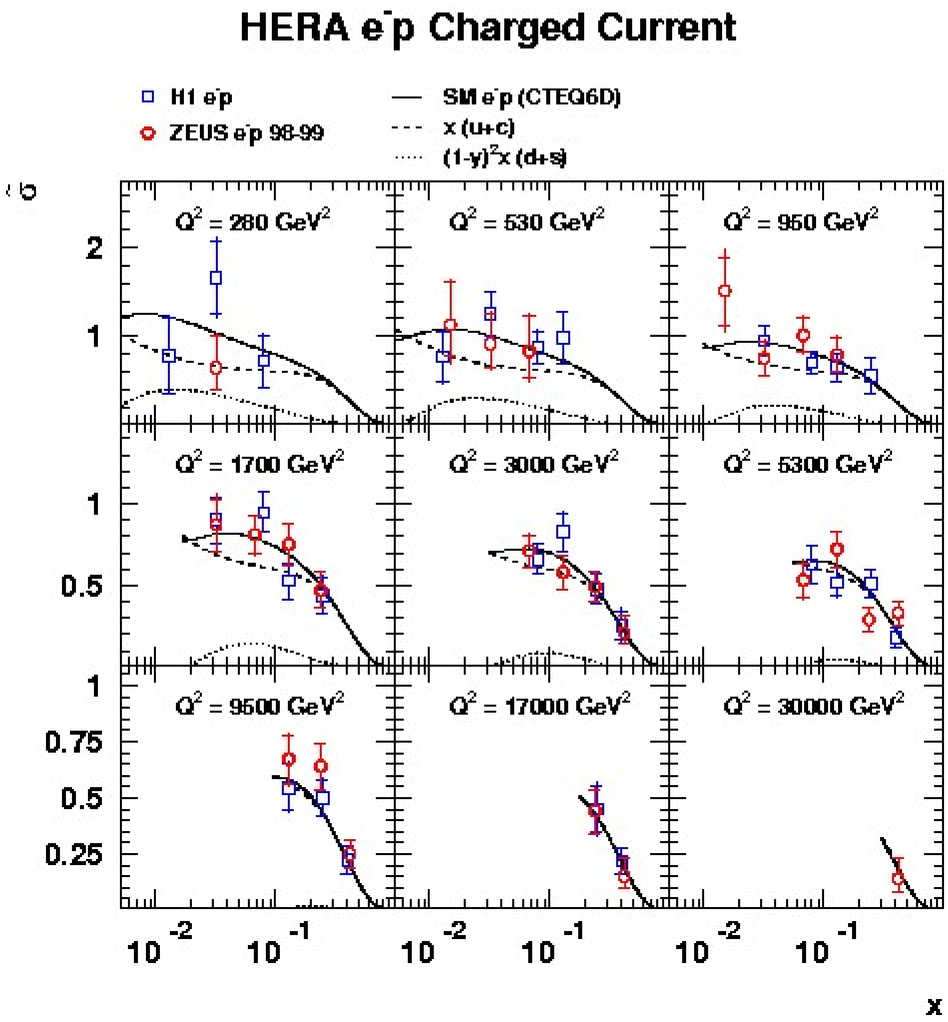




Agreement ZEUS, BCDMS
Agreement data and ZEUS-S
Agreement ZEUS, H1
Agreement data CTEQ6

Statistics will be improved with the HERA II data





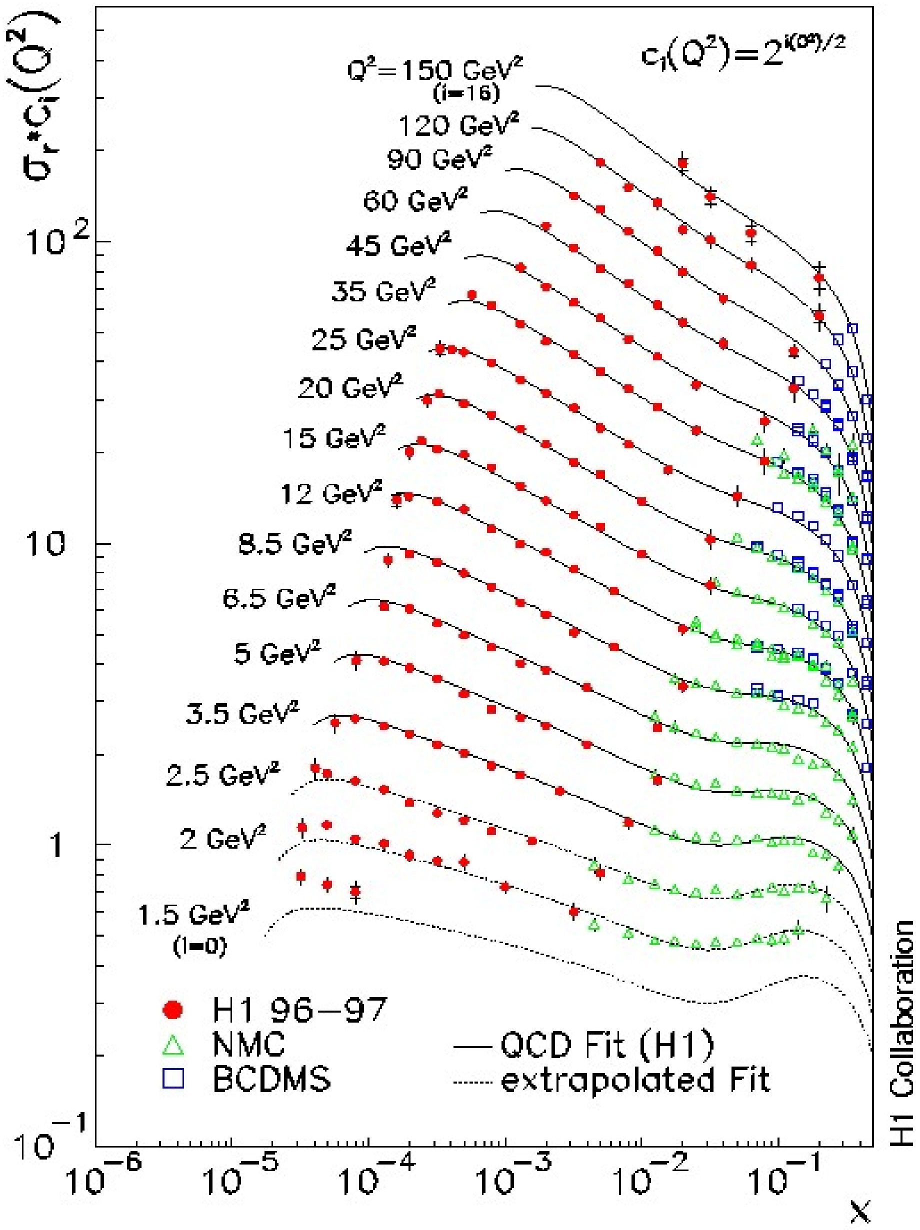
$$\tilde{\sigma}^{+}_{CC} = x[\overline{u} + \overline{c} + (1-y)^2(d+s)]$$

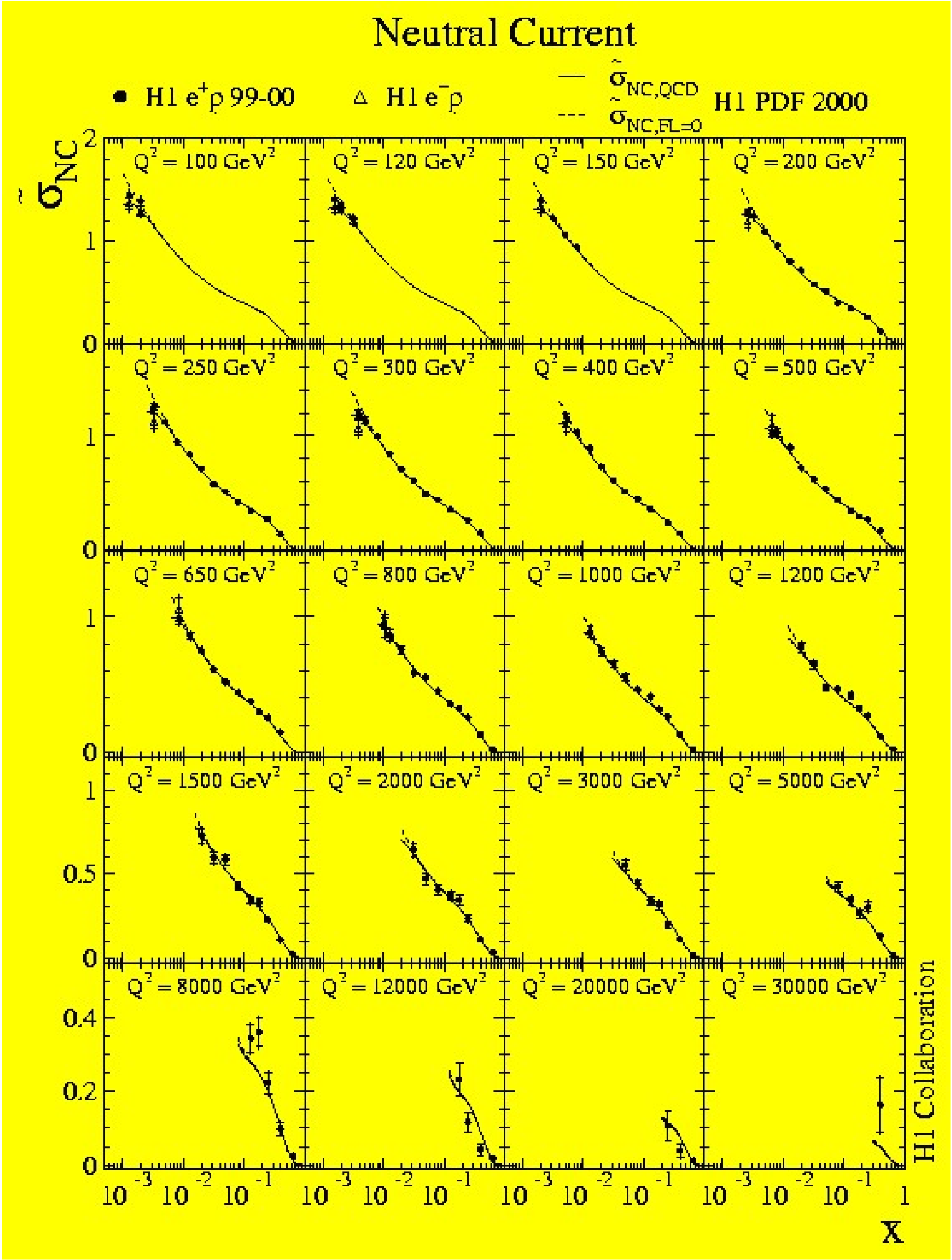
$$\tilde{\sigma}^{-}_{CC} = x[u + c + (1-y)^2(\overline{d} + \overline{s})]$$

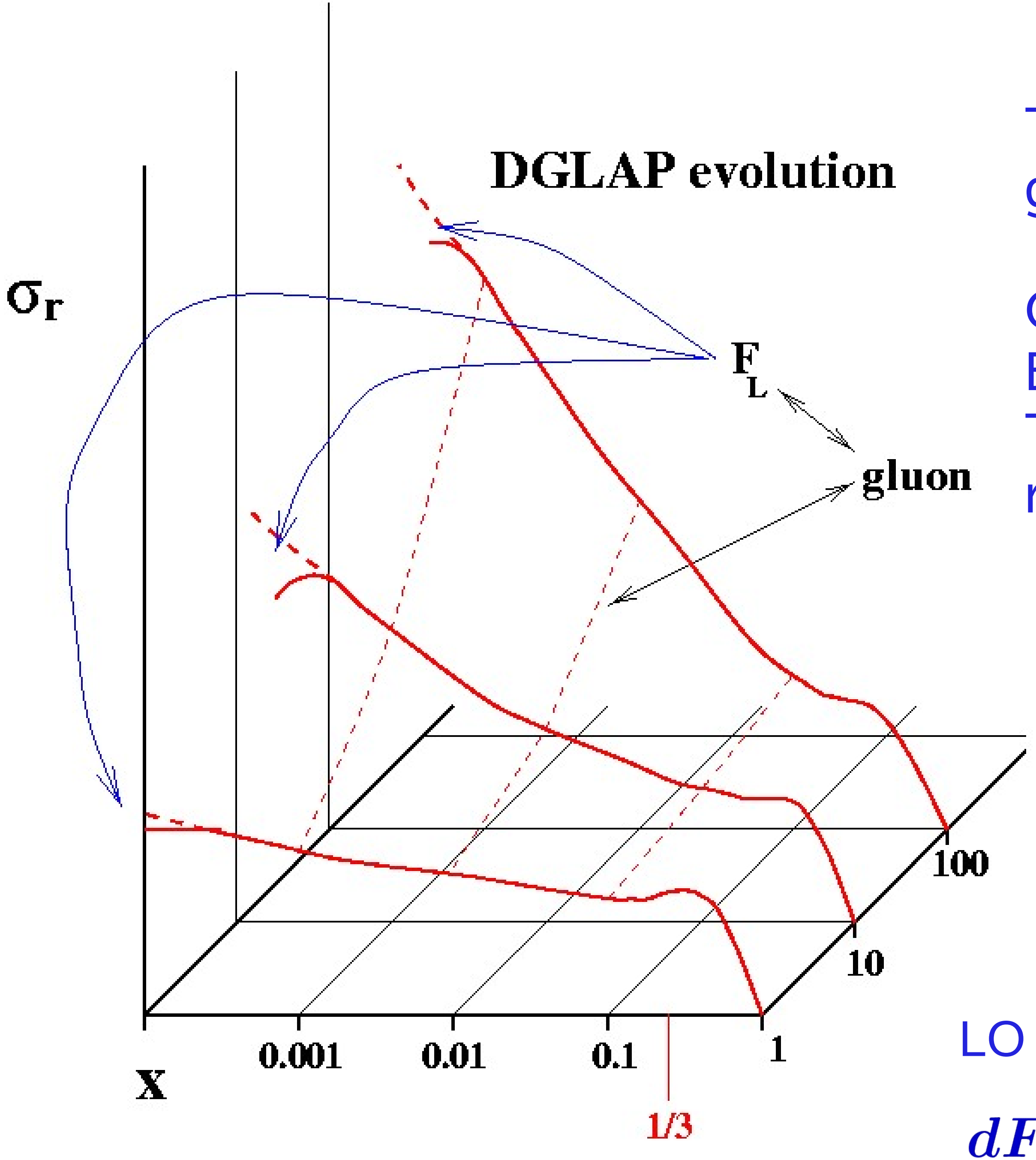
e+p data sensitive to d-quark, e-p data to u-quark distributions

Both e+p and e-p data needed for flavour separation

NC DIS: Reduced cross section measurements







The larger Q^2 is, the more gluons are seen at low x

Gluons split into $q\bar{q}$
But $F_2 \propto x(q+\bar{q})$
Thus the gluon “drives” the rise of F_2 at low x

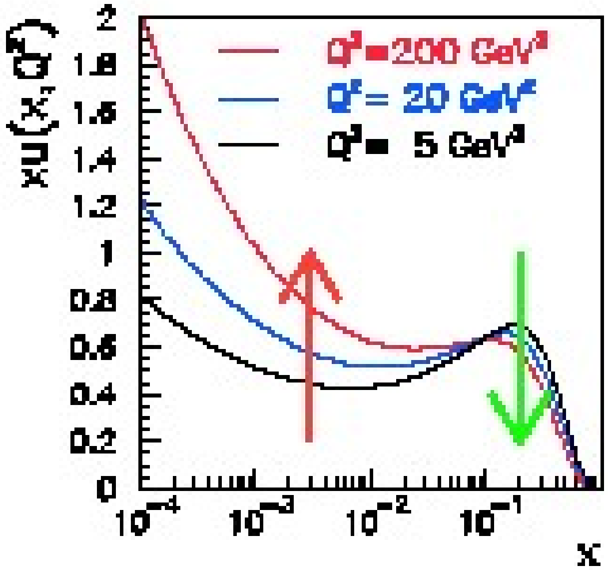
The dotted lines represent the Scaling Violations, given by the increasing gluon density

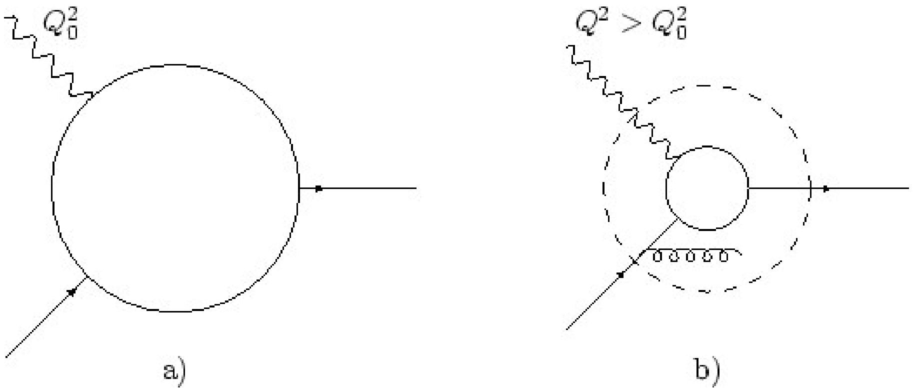
LO DGLAP, low x:

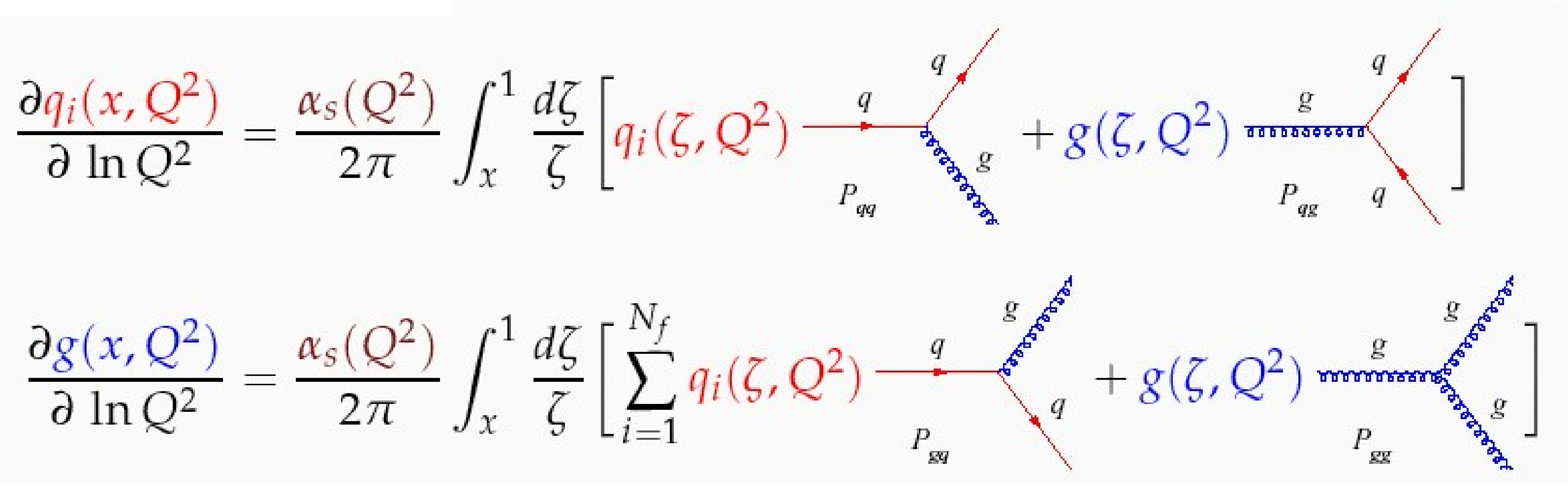
$$dF_2/d\ln Q^2 \sim \alpha_s x g(x)$$

DGLAP Evolution

Dokshitzer, Gribov, Lipatov, Altarelli, Parisi







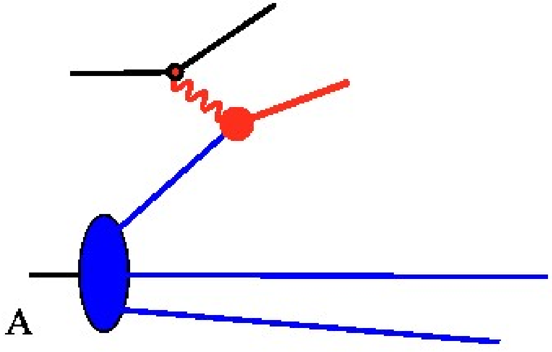
$$\frac{\partial q_i(x,Q^2)}{\partial \ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 \frac{d\zeta}{\zeta}\left[q_i(\zeta,Q^2) + g(\zeta,Q^2)\right]$$

$$\frac{\partial g(x,Q^2)}{\partial \ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\int_x^1 \frac{d\zeta}{\zeta}\left[\sum_{i=1}^{N_f} q_i(\zeta,Q^2) + g(\zeta,Q^2)\right]$$

QCD Splitting functions: With increasing Q^2, probability increases for a parton to split into new partons with lower x

Parton Distribution (Density) Functions, PDFs

Give the probability to find partons in a hadron, as a function of the fraction x of the proton's momentum, carried by the parton ✭



The cross section factorizes into a convolution of parton distributions, and the parton-parton cross section

$$d\sigma \sim \sum_a \int dx_A \, f_{a/A}(x_A, \mu) \, d\hat{\sigma}$$

The parton level cross section, $d\hat{\sigma}$, is calculable in perturbative QCD

The PDFs cannot be calculated in pQCD.
They have to measured, i.e. extracted from experimental data,
using methods based on pQCD

PDFs depend on the way of extracting them: NLO, NNLO, etc.

✭ http://**zebu.uoregon.edu**/~soper/soper.html/

QCD analysis of the data: The H1 and ZEUS NLO-QCD fits

Recipee: 1. Measured (reduced) cross sections in bins of Q^2 and x

2. Parameterise PDFs for each parton, as function of x and valid at a starting value of $Q^2 = Q_0^2$

General form:

$$xP(x) = p_1 x^{p_2}(1-x)^{p_3}[1 + p_4 x + p_5 x^2 + p_6 x^3 + p_7 x^4]$$

3. Apply DGLAP evolution and fit to the data

$$\frac{\partial}{\partial \log\left(Q^2 / \mu_F^2\right)} \begin{pmatrix} q^{SI} \\ xg \end{pmatrix} = \frac{\alpha_S(\mu_R^2)}{2\pi} \begin{pmatrix} P_{qq} & P_{qg} \\ P_{gq} & P_{gg} \end{pmatrix} \otimes \begin{pmatrix} q^{SI} \\ xg \end{pmatrix}$$

4. Keep going till the PDF parameterisation is optimal !

H1 and ZEUS use similar strategies, although there are many differences in details. However, the results are very similar, and both fits describe the data very well.

QCD analysis of the data: The H1 and ZEUS NLO-QCD fits

Some main differences:

H1 use the Fixed Flavour Number (FFN) scheme, with massless quarks

ZEUS use the RT-VFN (Varied Flavour Number - Roberts,Thorne), for smooth transition in the handling of the heavy quark part above mass threshold

ZEUS make use of all fixed target data (NMC,BCDMS,E665,CCFR,SLAC)
H1 use only BCDMS

Different assumptions on the definition of valence and sea quarks, on their detailed parameterisation and on the starting value, Q_0^2

The global fits and their data

MRST

Martin,Roberts,Stirling,Thorne

CTEQ

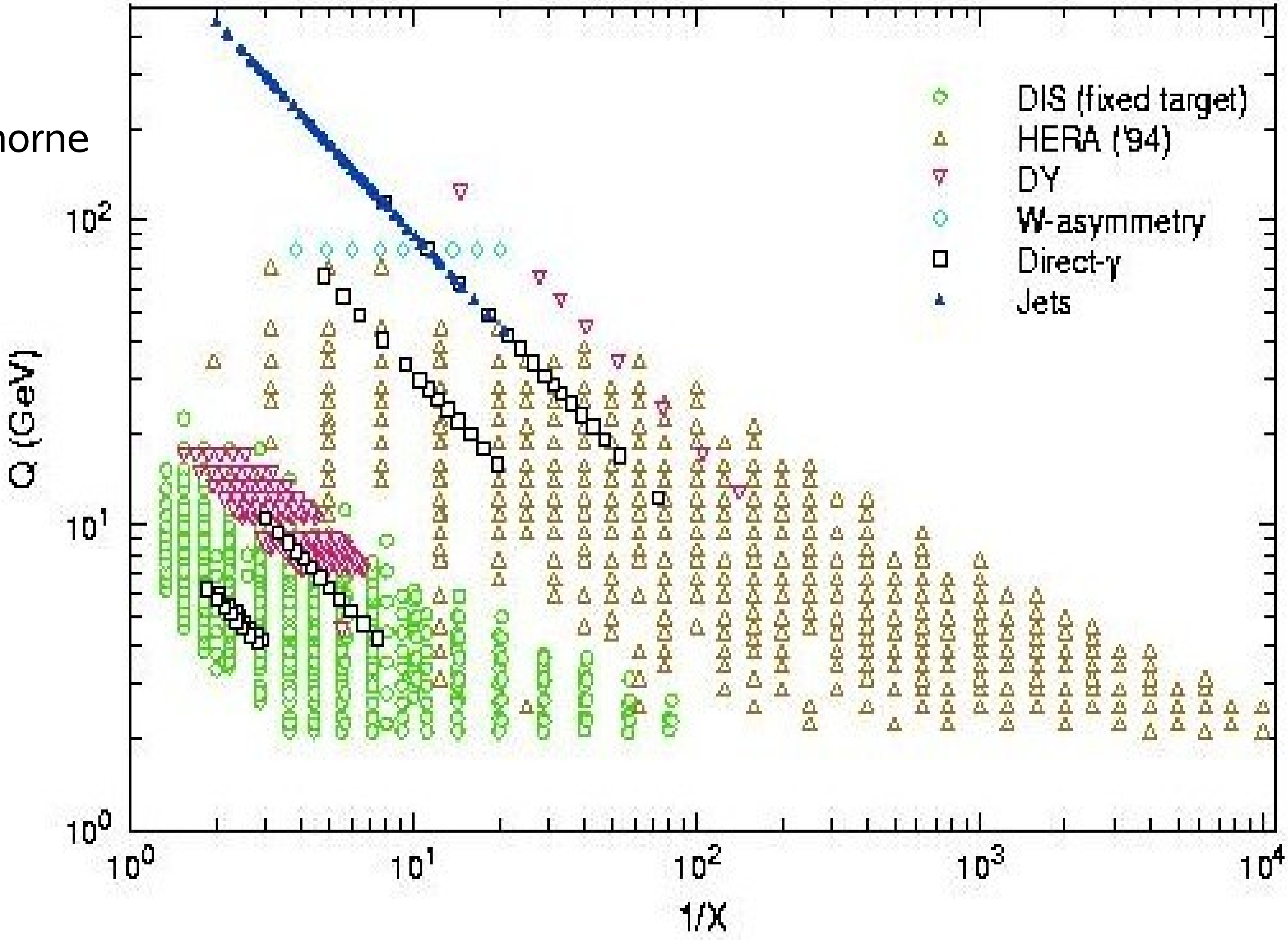
Pumplin et al.

GRV

Glueck, Reya, Vogt

H1 and ZEUS,

using mainly HERA data



QCD analysis of the data: The H1 and ZEUS NLO-QCD fits

Both collaborations performed several fits:

Zeus Fits : **ZEUS-S**tandard

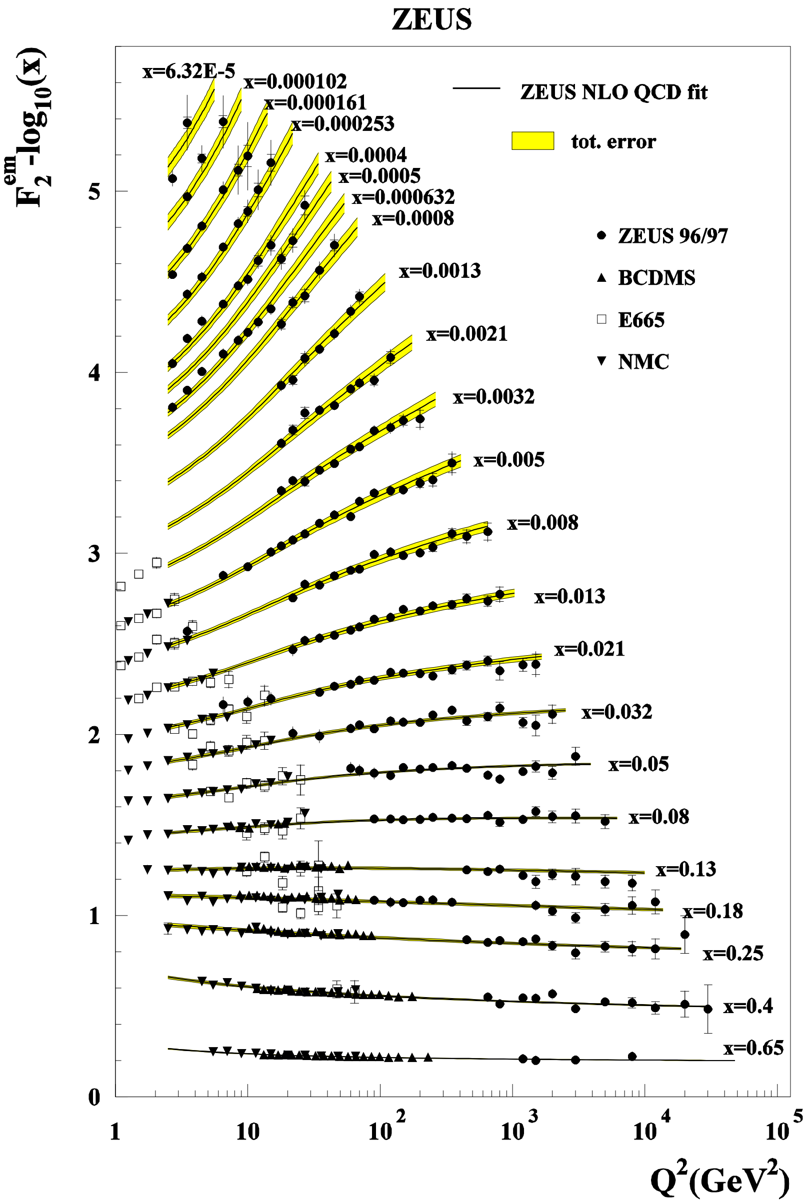
Use Zeus NC 96/97 e^+
BCDMS, NMC, E665 proton data
NMC,E665 deuterium data, CCFR xF_3 iron data
For high x constraint, better flavour separation

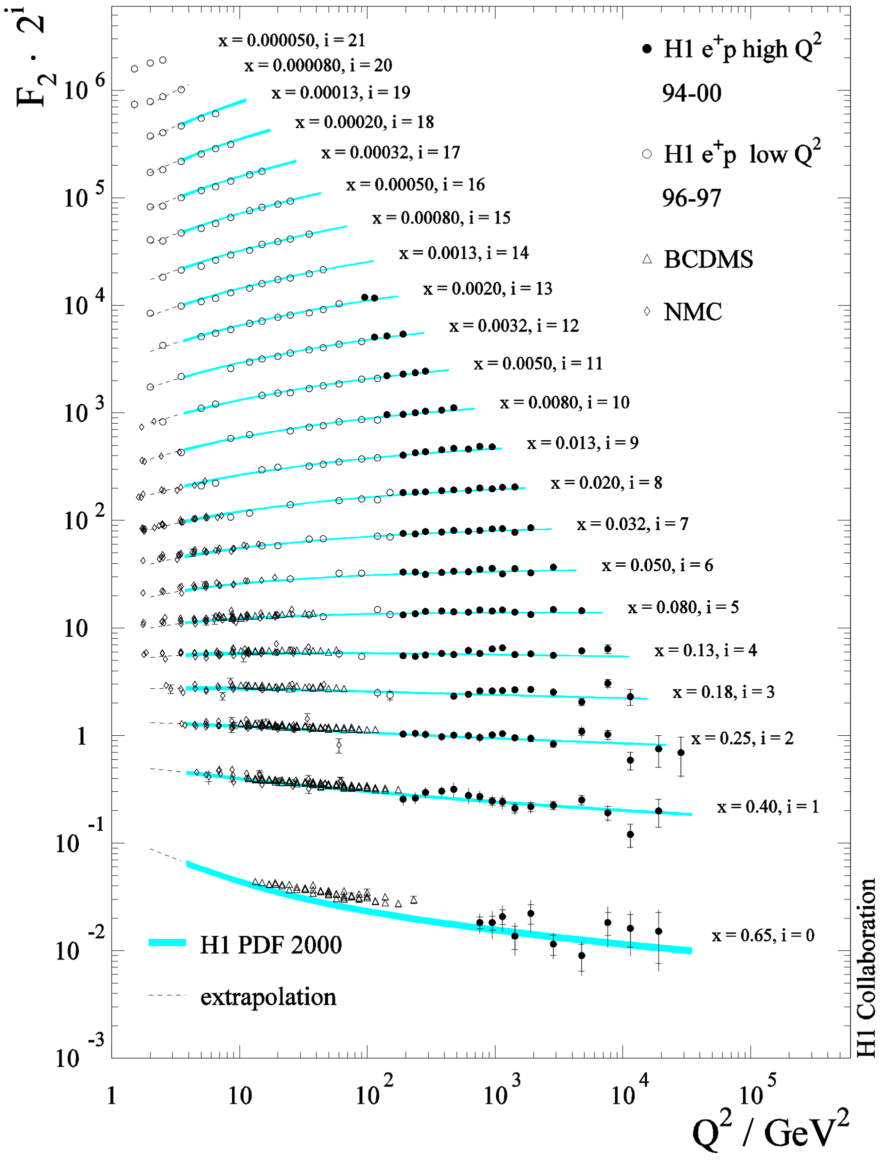
ZEUS-Only
Use only Zeus data NC and CC e^+ and e^- up to 99
The nr. of d.o.f. reduced by fixing parameters
Both use TR Variable Flavour Number Scheme

H1 Fits: **H1PDF2000** and H1 + BCDMS μp

Use only H1 data (all HERA I NC and CC)
Massless Fixed Flavour Number Scheme

The Result!

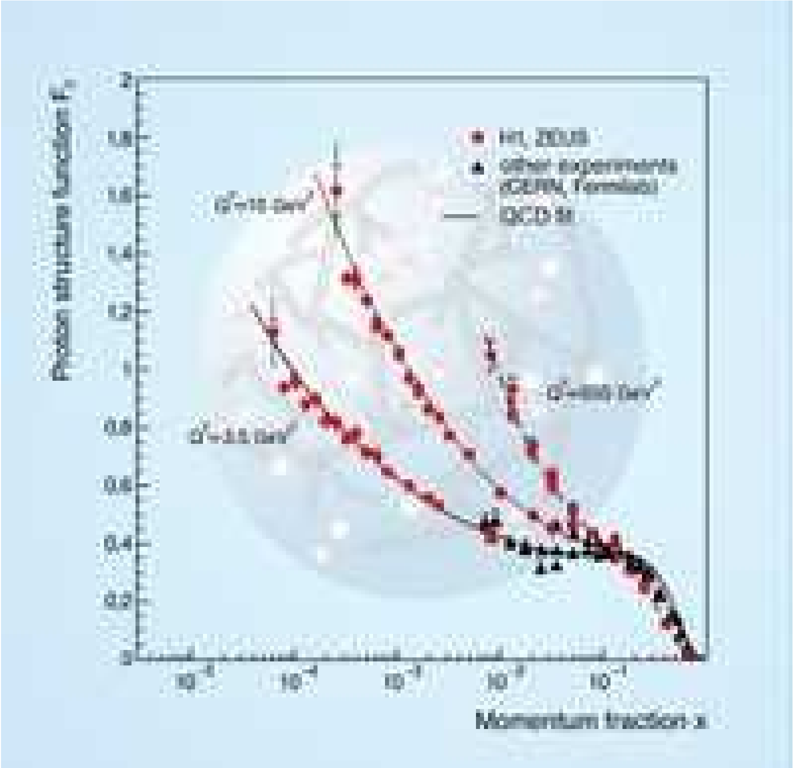


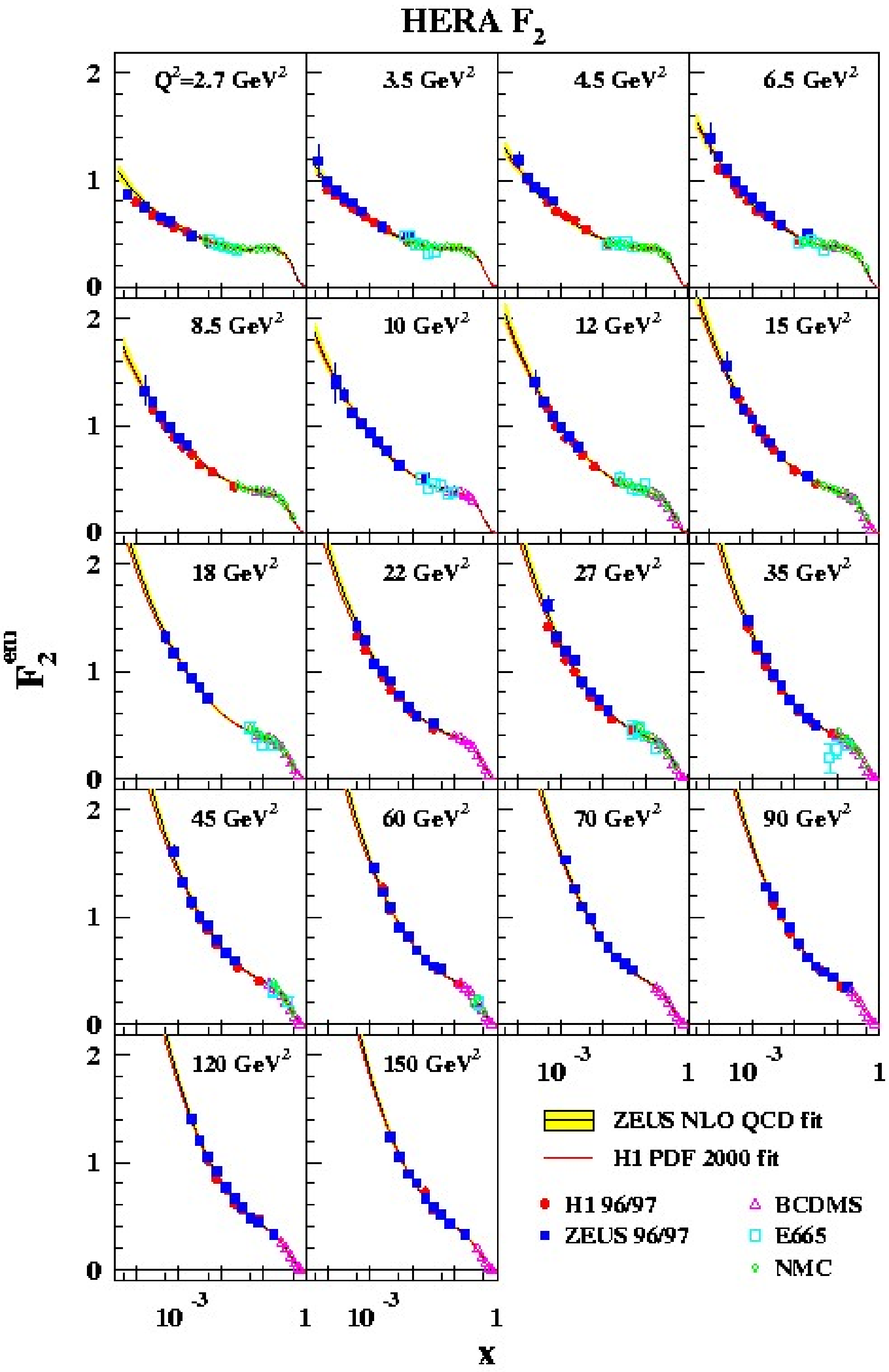


NLO QCD describes data over >4 orders of magnitude in Q^2 and x !

Fit works well even for very low Q^2 and x ! (~1 GeV^2, ~0.00005)

The H1 and ZEUS NLO-QCD fits



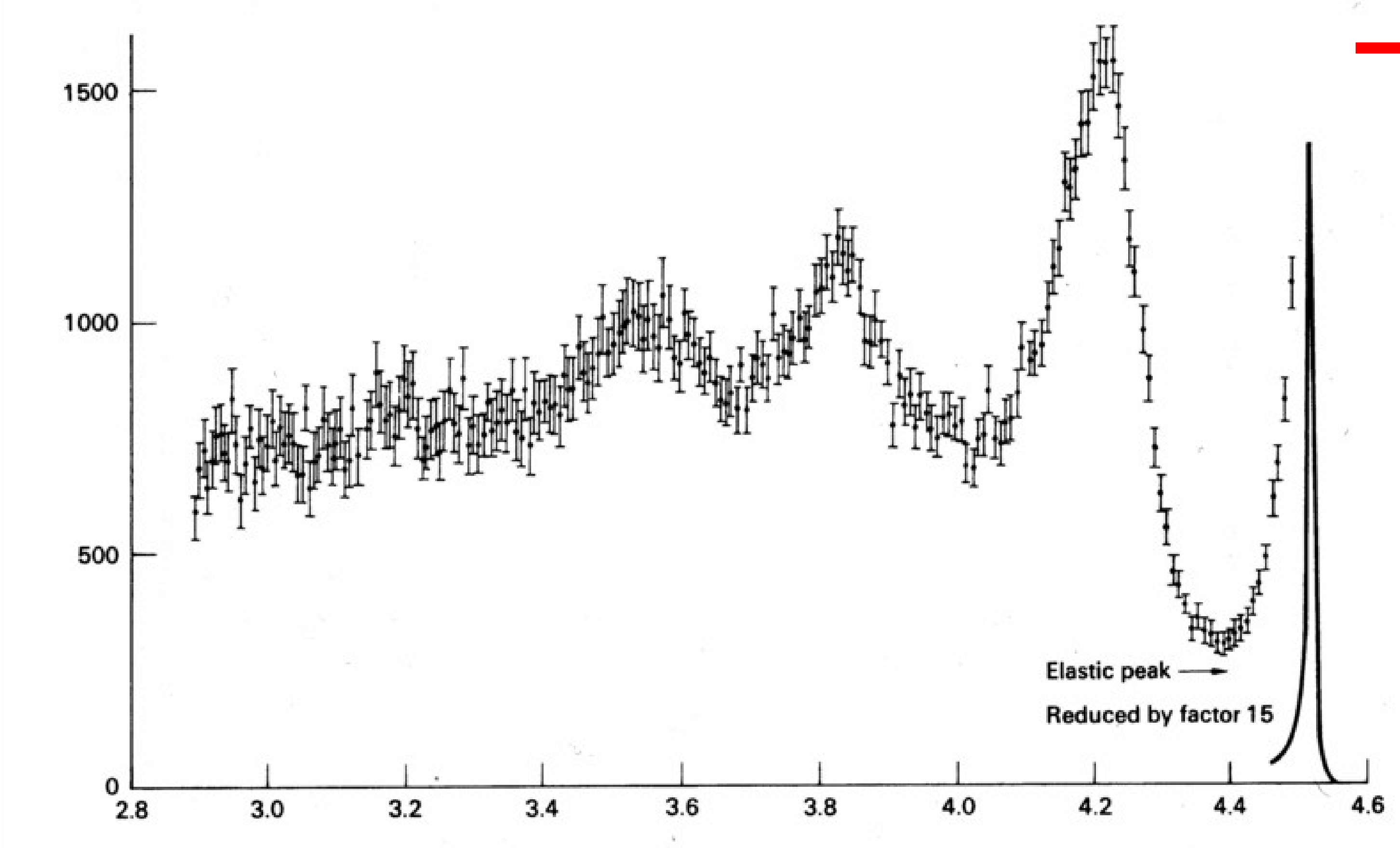


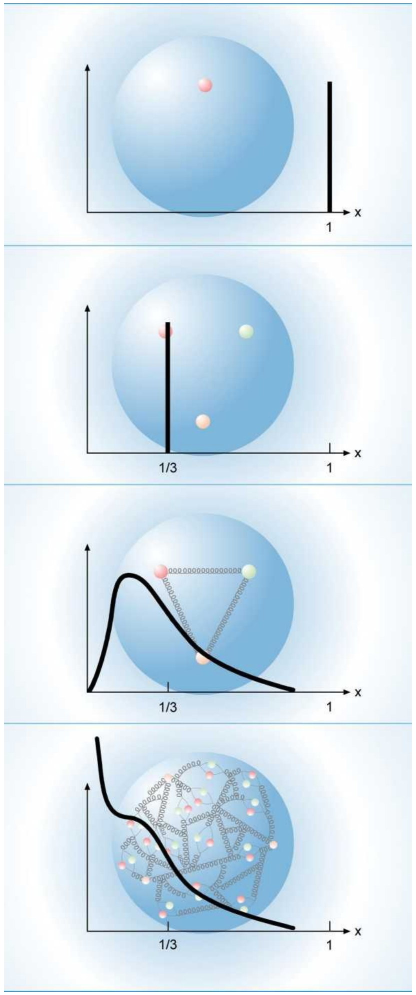
Now a textbook plot!

the dramatic increase of the gluon density at small x in the proton, is one of the most significant discoveries at HERA!

A quick look back on history

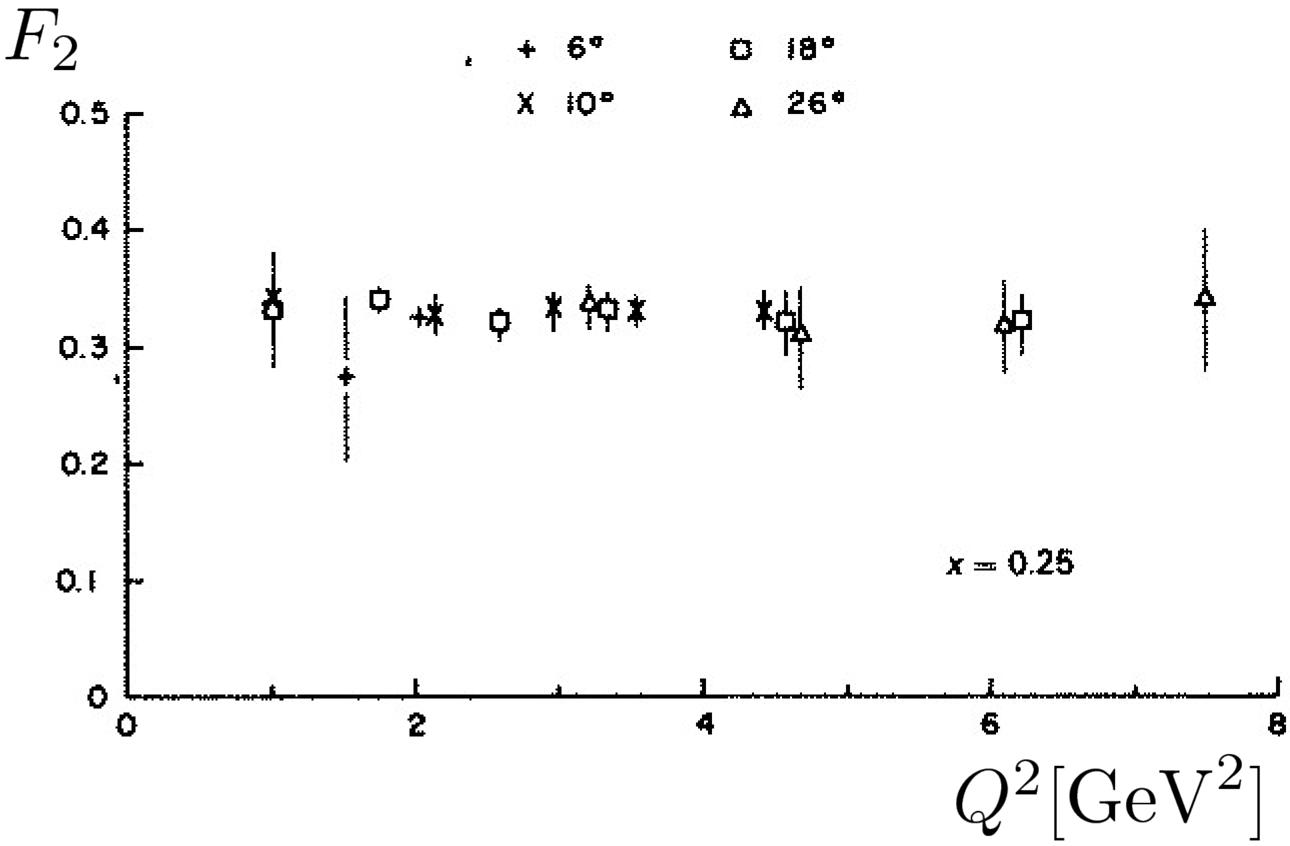
DESY 1968, E_{beam} = 4.9 GeV, fixed target

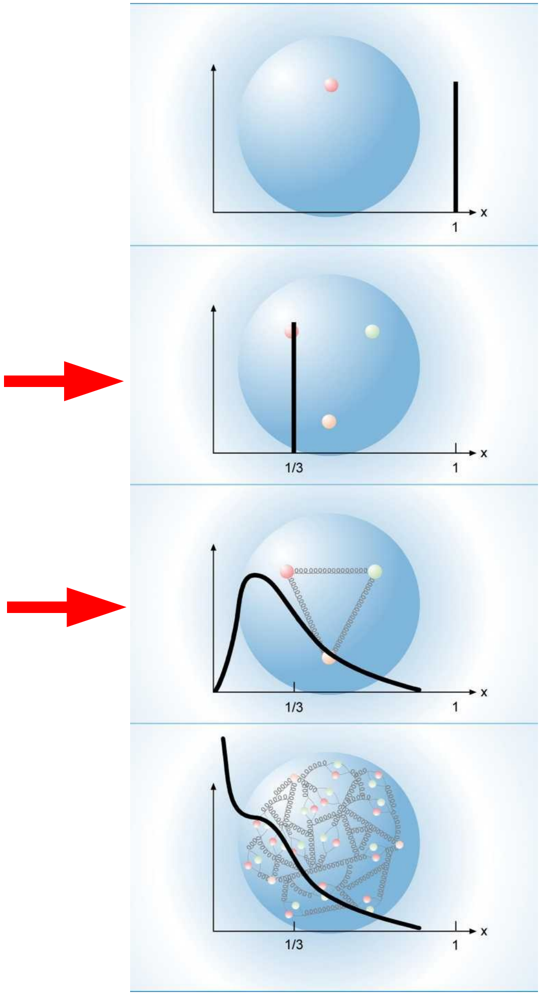




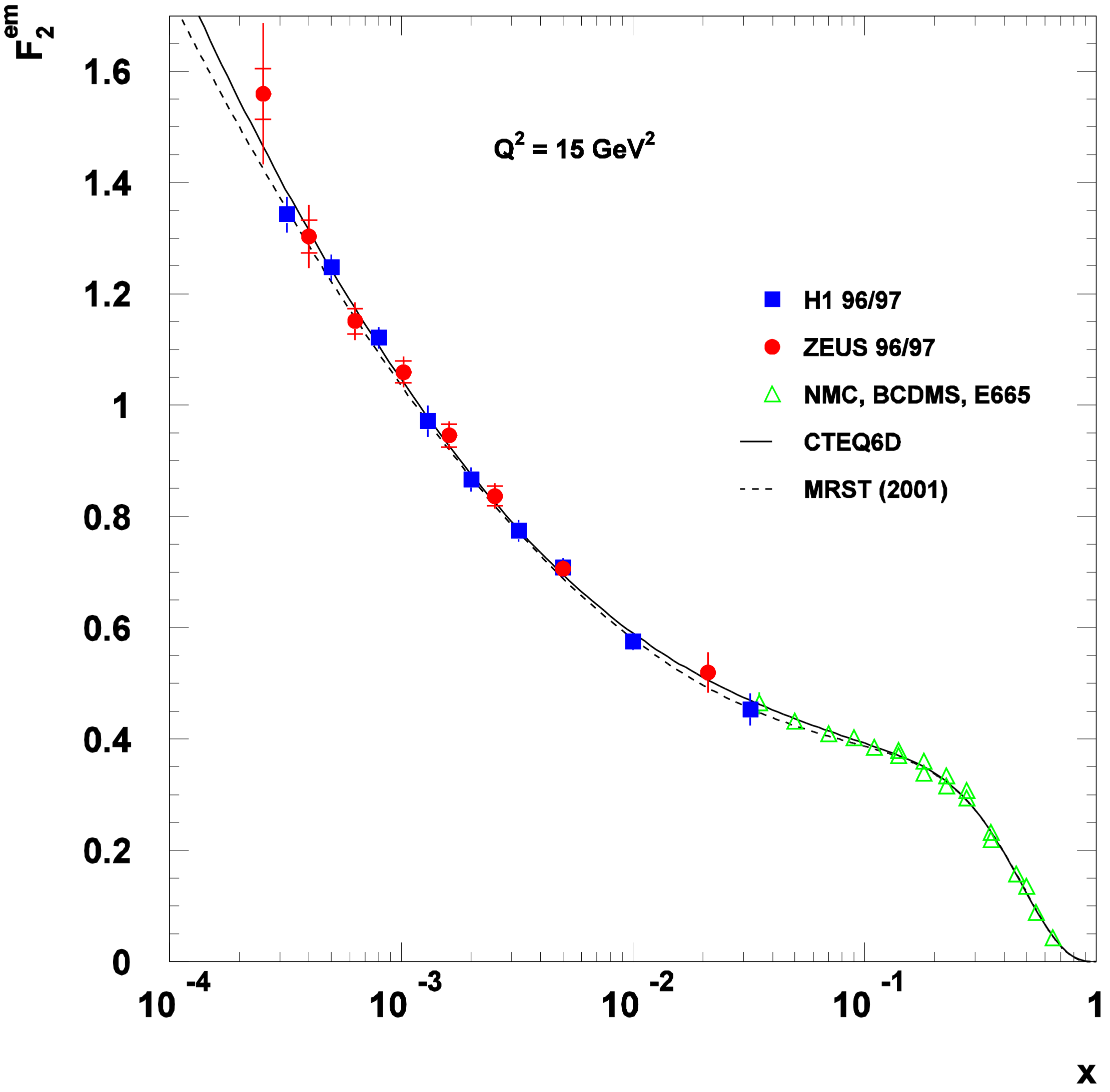
A quick look back on history

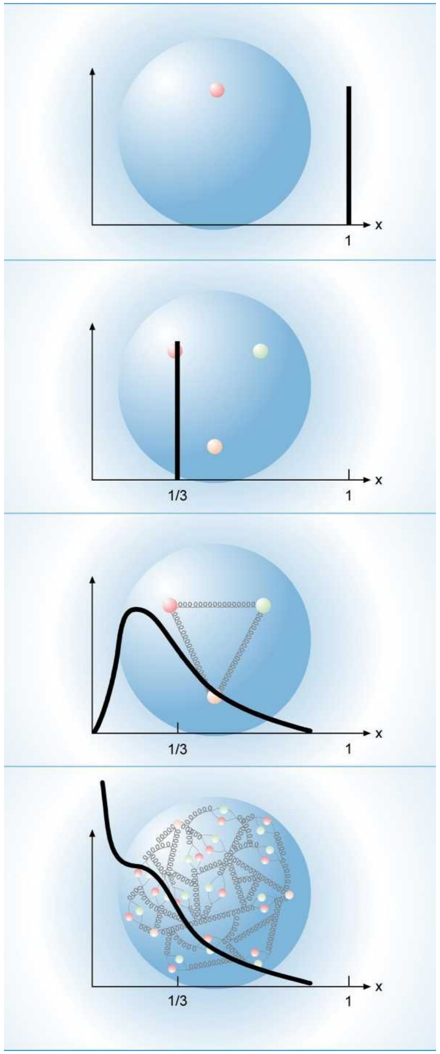
Scaling, observed at SLAC 1968



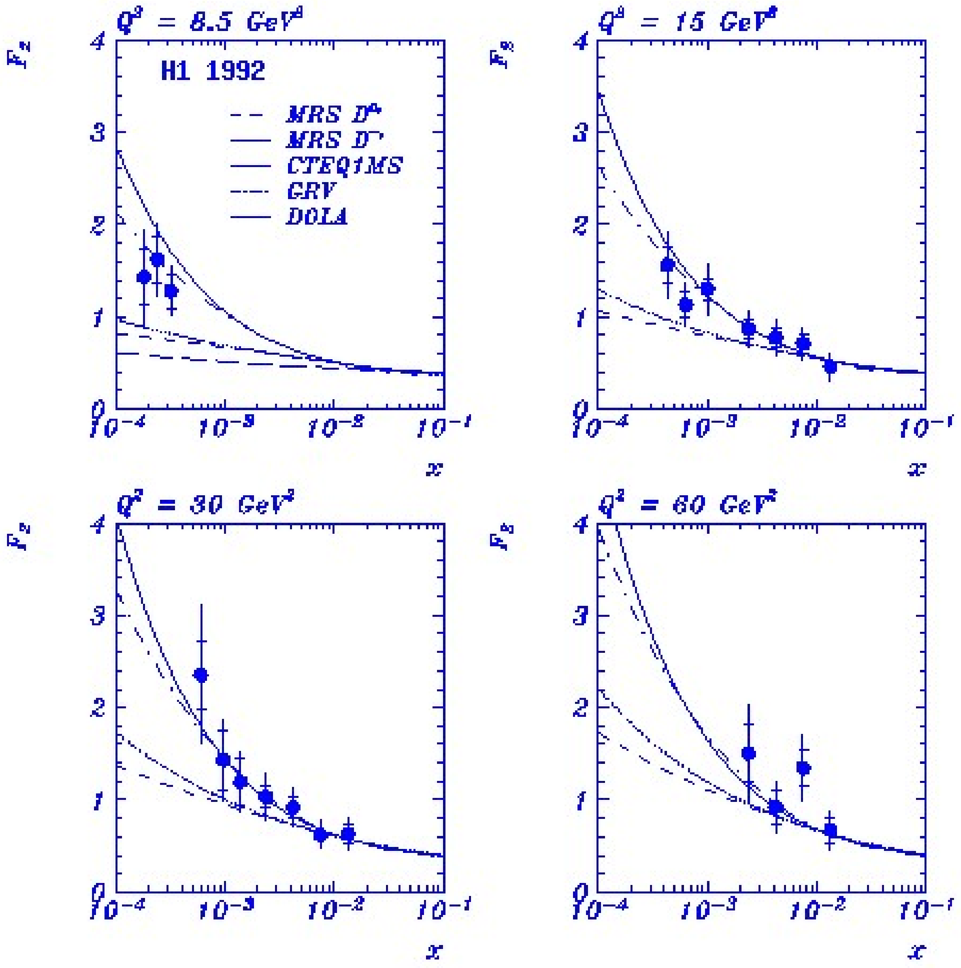


Proton structure at low x finally revealed at HERA

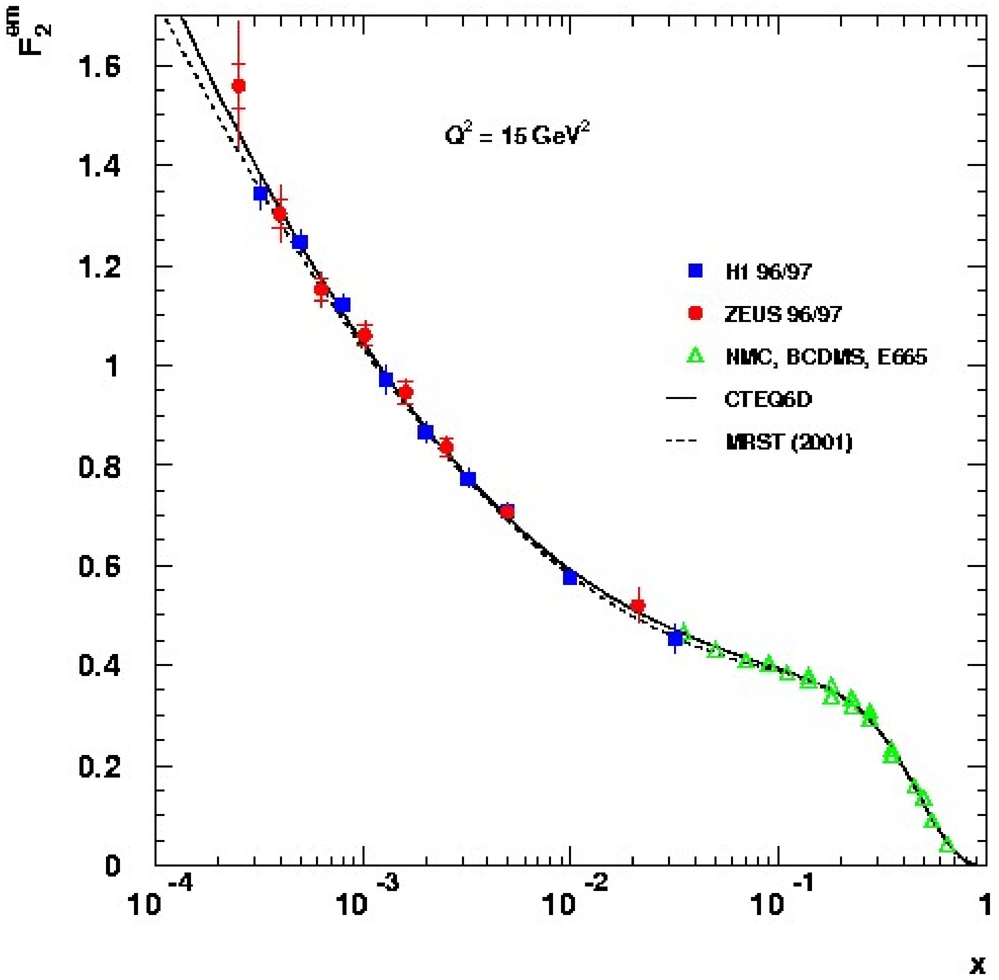




The first HERA data...



And 5 years later



The first HERA data already discriminate among theoretical models!

Physics Nobel Prize 2004

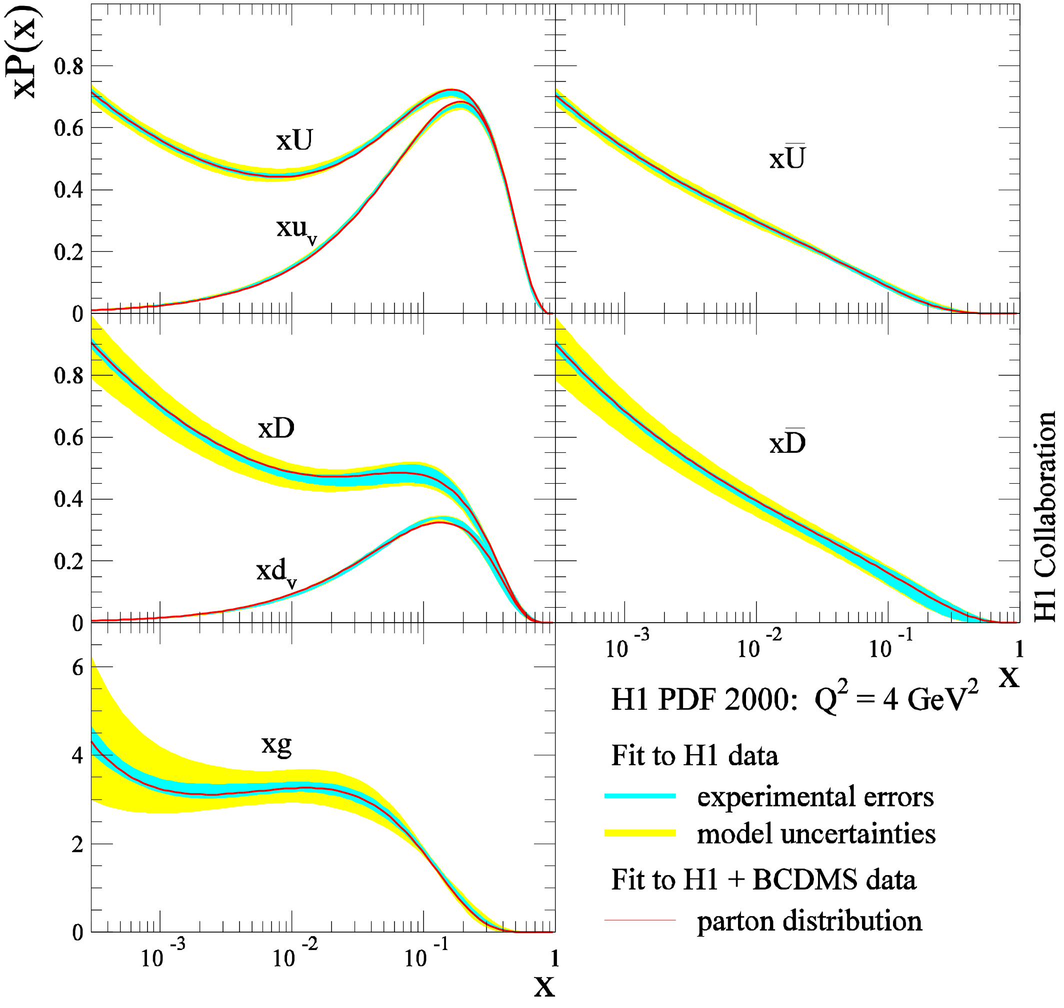

David Gross David Politzer Frank Wilczek

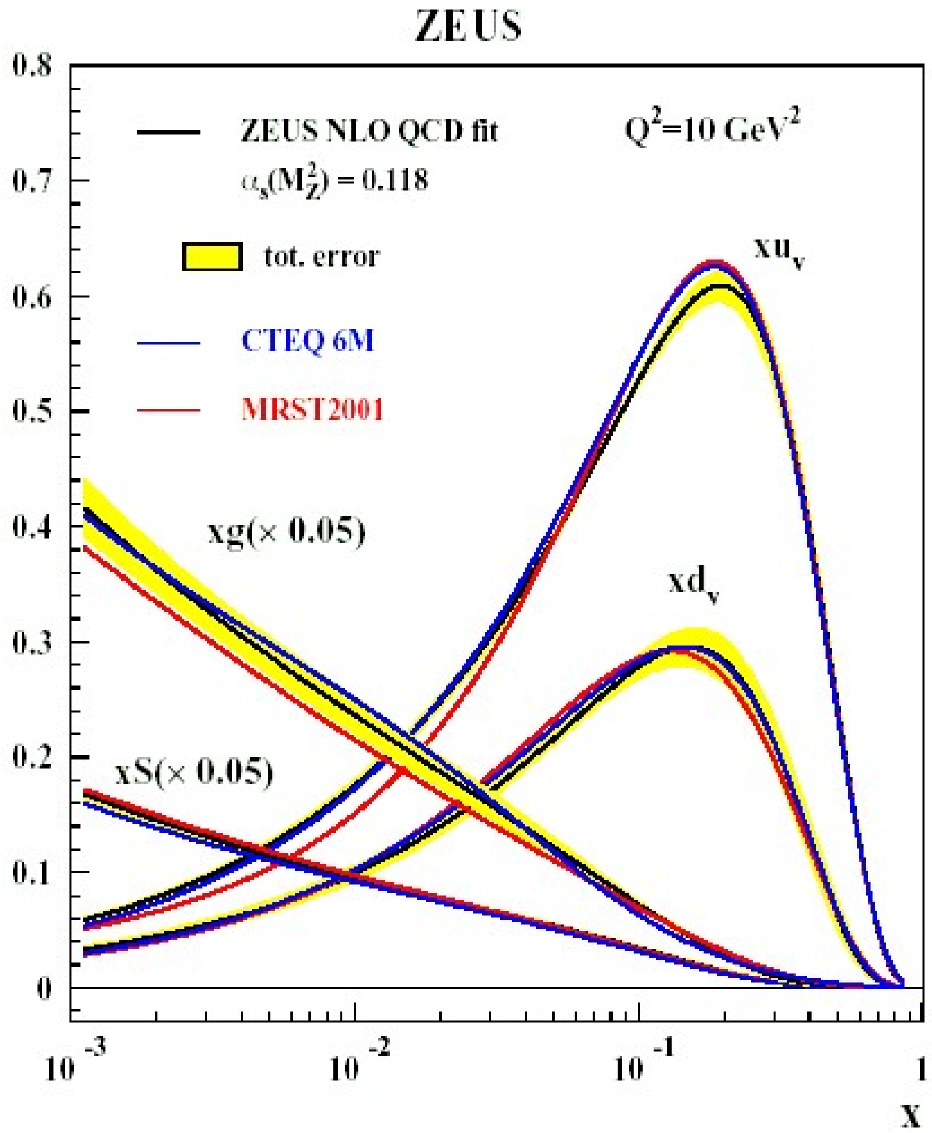
"For the Discovery of
Asymptotic Freedom in
the Theory of Strong Interactions"

Frank Wilczek:

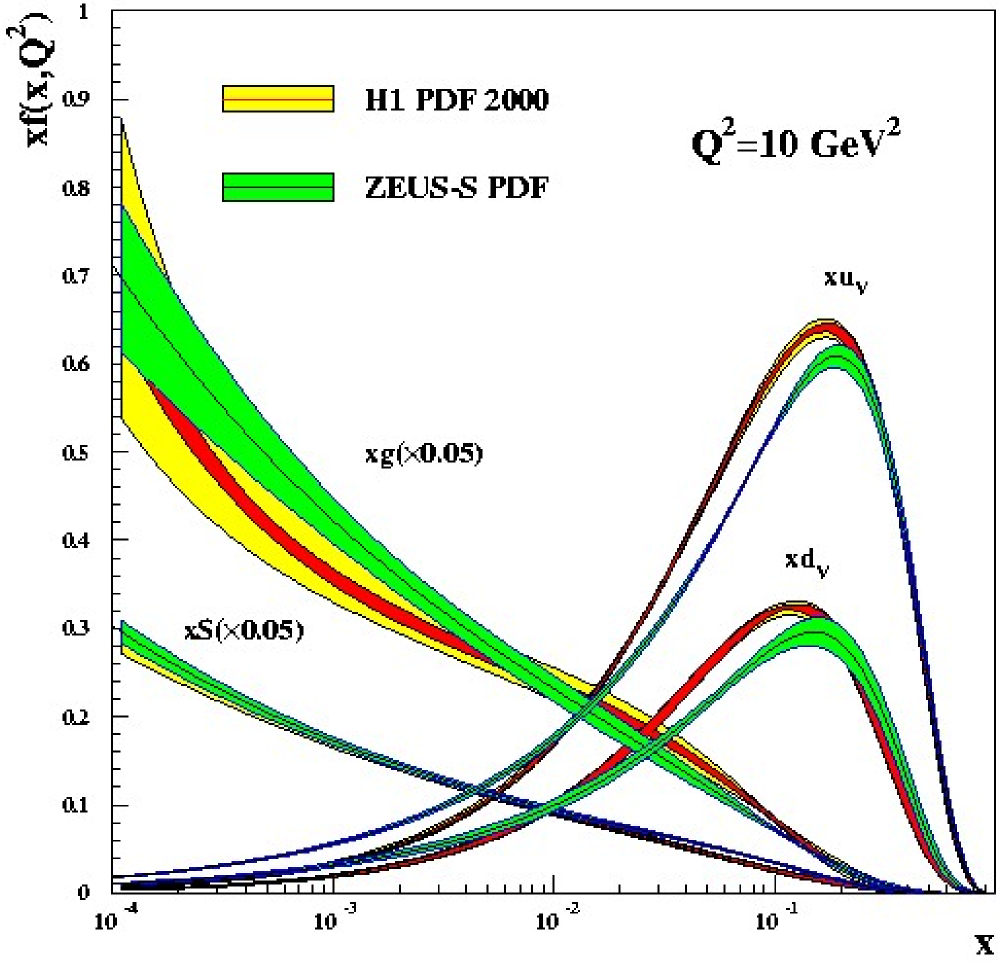
> "The most dramatic of these (experimental consequences), that protons viewed at ever higher resolution would appear more and more as field energy (soft glue), was only clearly verified at HERA twenty years later"

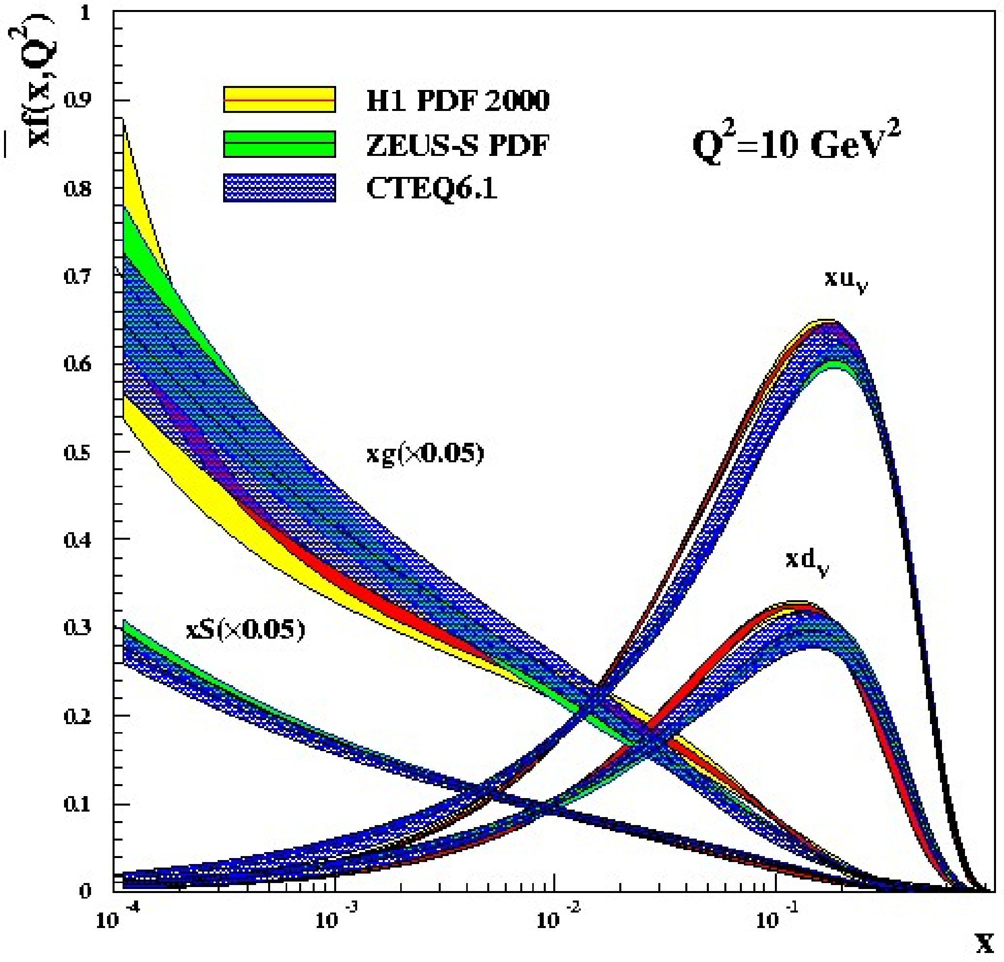
Parton distributions from the fits:





Comparison of Parton Distributions from the fits

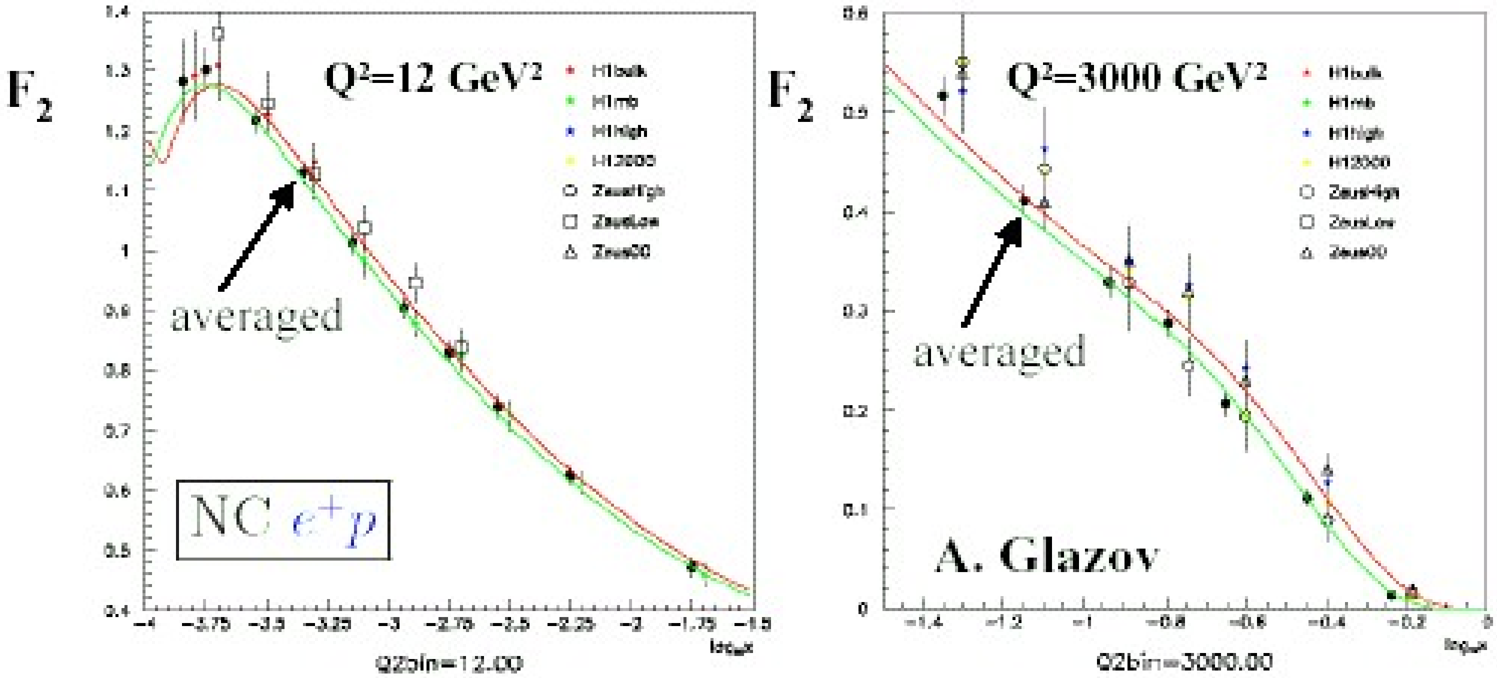




Small differences seen between H1 and ZEUS,
outside of the quoted error bands;
The CTEQ6 fit falls between H1 and ZEUS

Towards the combined HERA SF data

Aim: average the H1 and ZEUS published SF data
in the theory free manner



- service to HEP community
  - unique HERA data set
  - proper treatment of correlations between different data sets
- cross checks of systematics: H1 vs. ZEUS

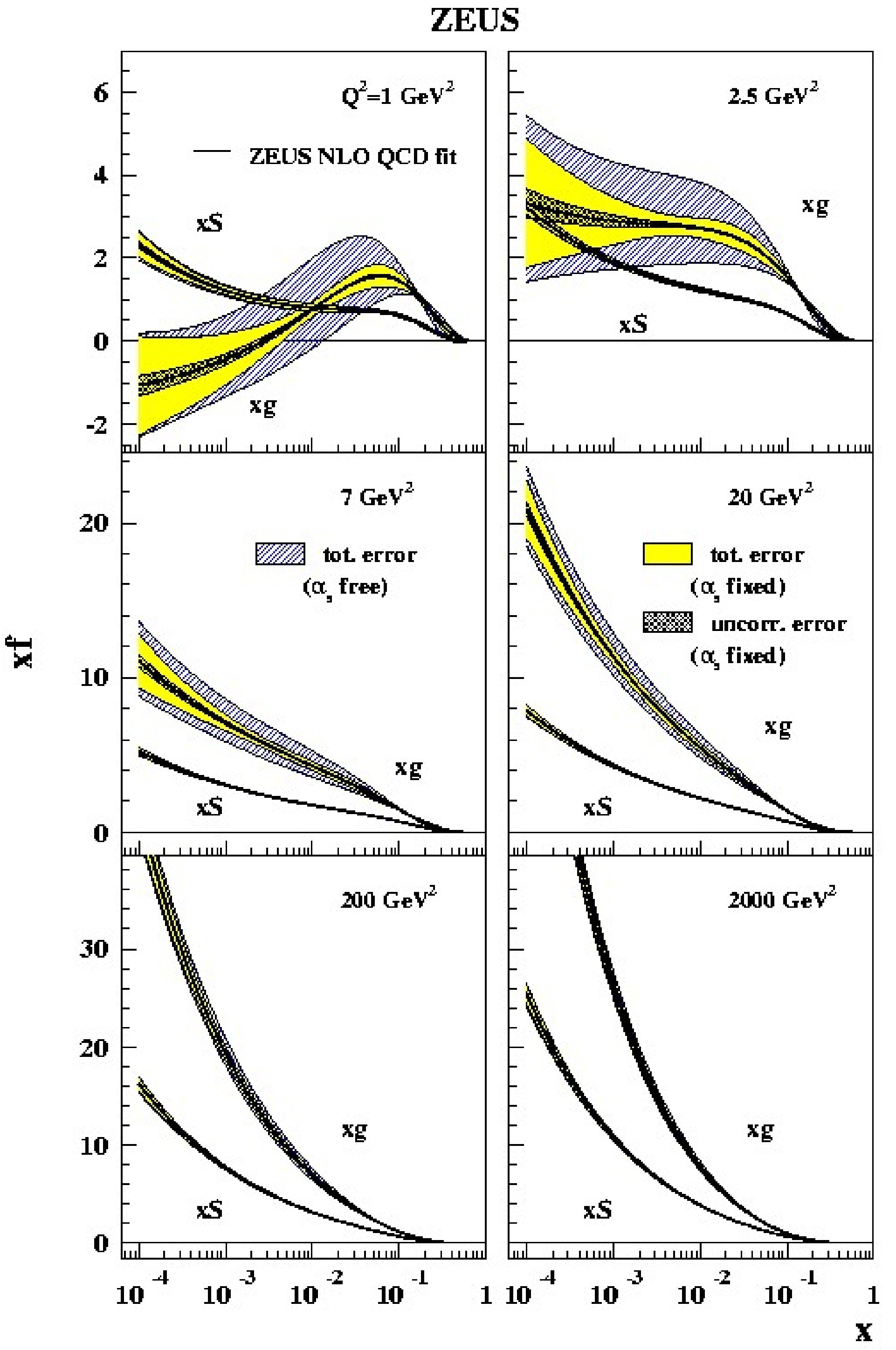
The "low Q^2" problem

At lowest Q^2 values, errors explode, and the gluon "goes negative"

Possible? The Gluon distribution is not an observable…

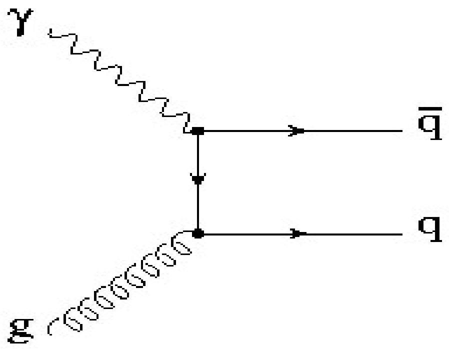
The gluon is only indirectly determinable, via the scaling violations in F_2

Need other data, with more direct constraints on the gluon

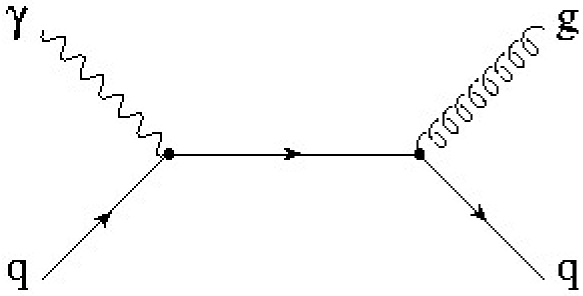


Including Jet data: The ZEUS-JETS NLO-QCD fit

BGF, Boson Gluon Fusion

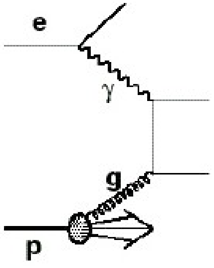


QCD-Compton

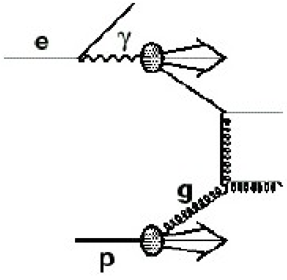


BGF: depends on xg(x) and α_s
QCDC: depends on q(x) and α_s

New constraints on gluon and α_s
Extract α_s and xg(x)
without strong correlation



Direct process



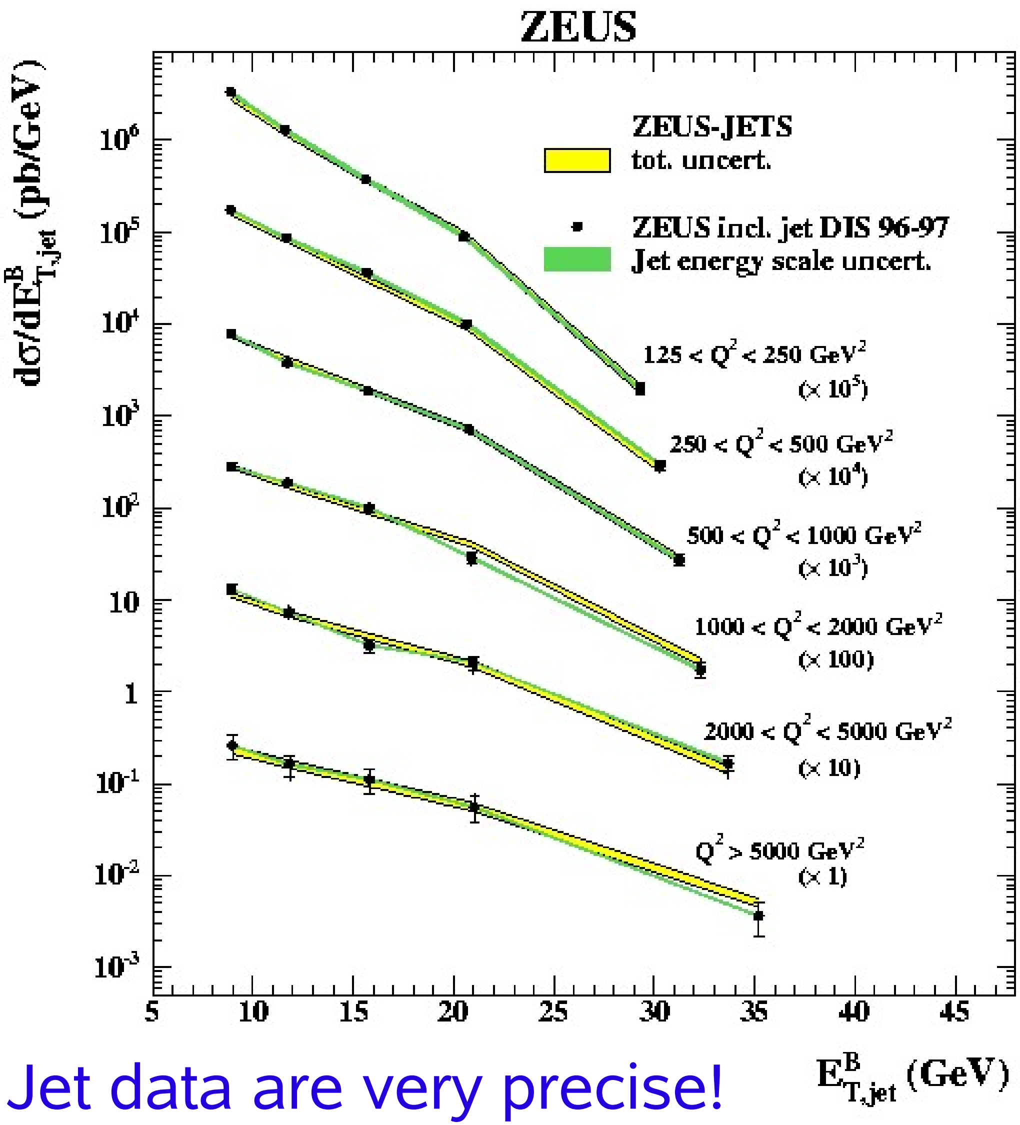
Resolved process

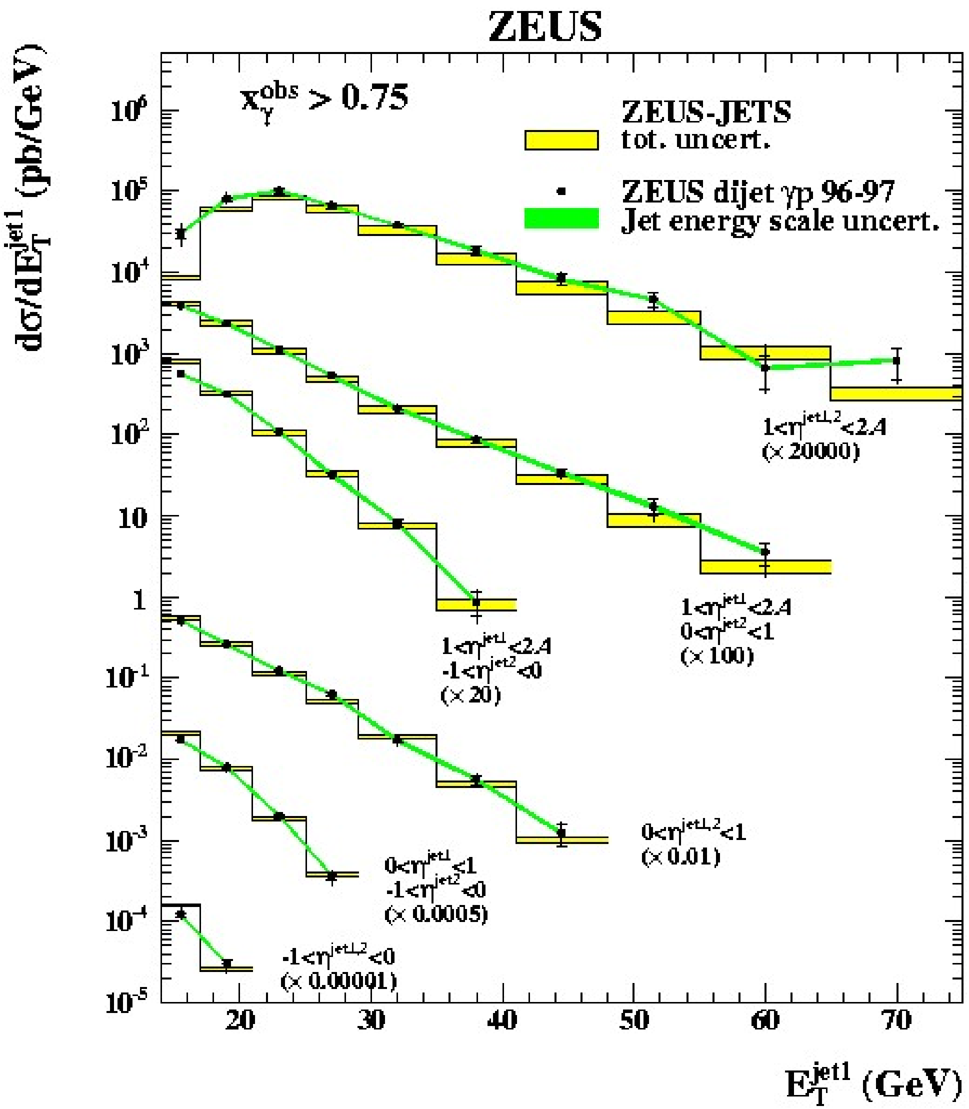
Use also Photoproduction dijet-events
Avoid complications from photon structure,
by cut

$$x_{\gamma}^{obs} > 0.75$$

(==> enrich direct photon dijet-events)

Including Jet data: The ZEUS-JETS NLO-QCD fit





Jet data are very precise!

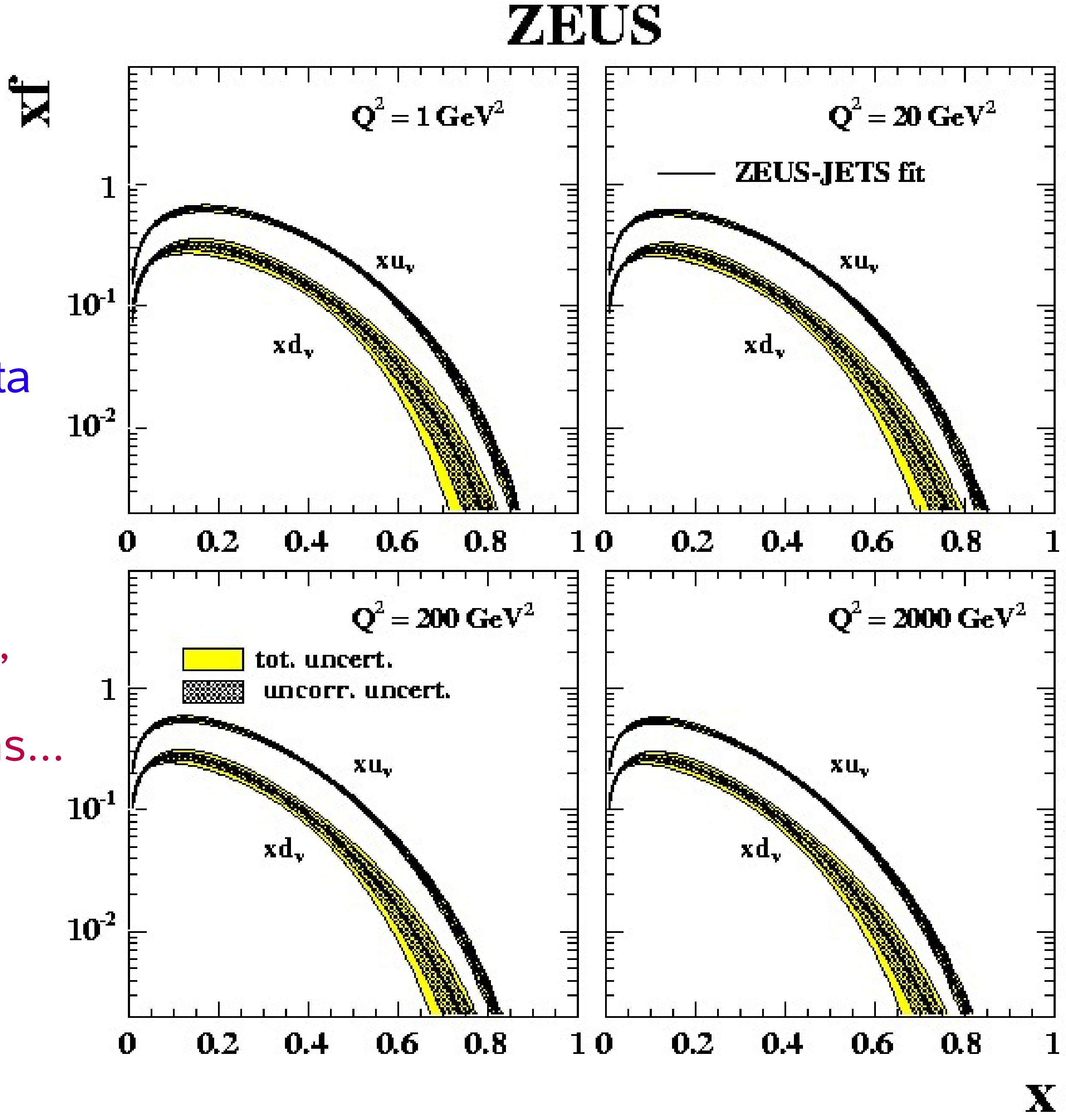
Fit calculations made via a grid of interpolation weights, obtained from pQCD calculations

Including Jet data: The ZEUS-JETS NLO-QCD fit

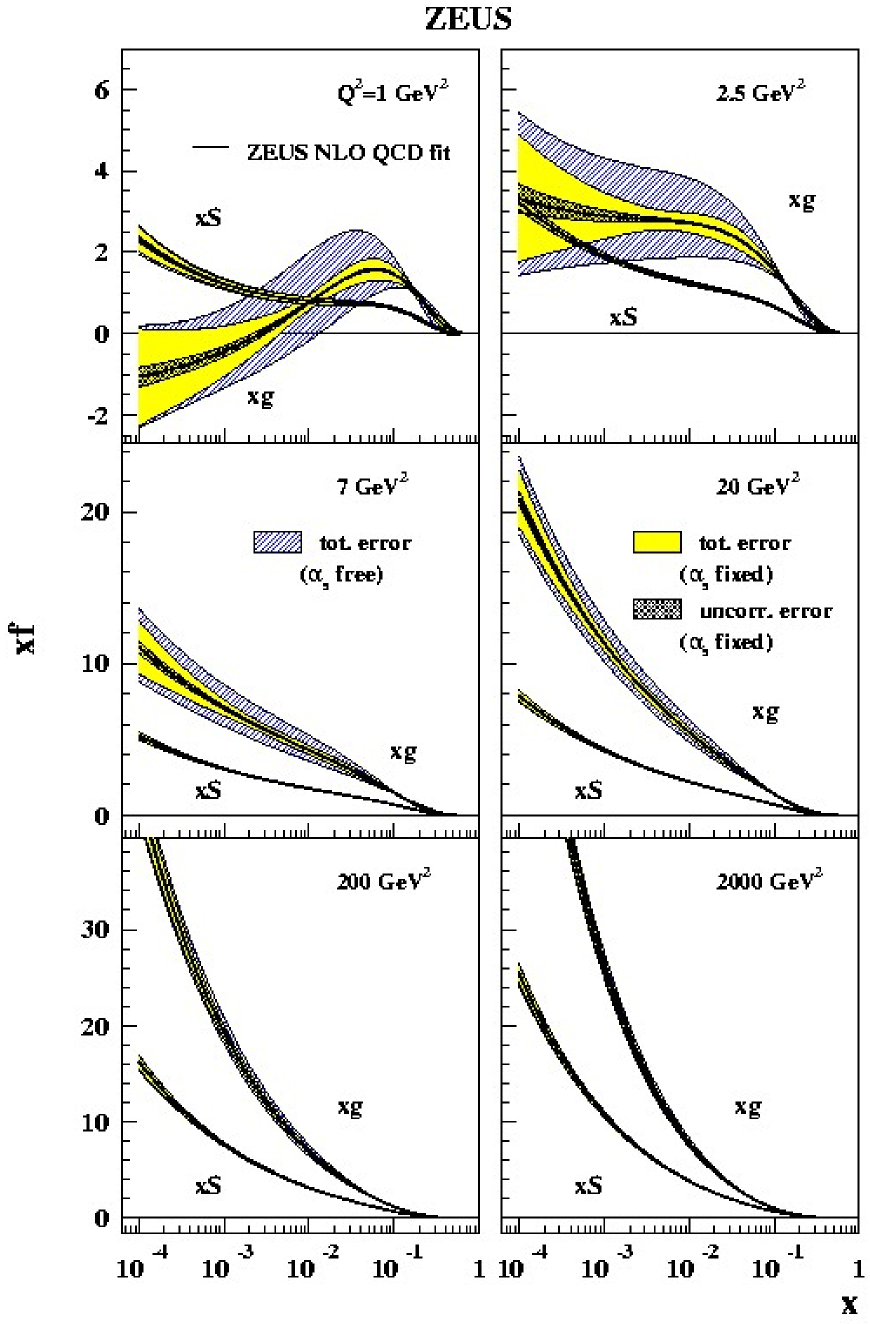
Valence distributions:

More precise than previous ZEUS-O distributions, but not so well constrained as when including fixed-target data

Fit uses only ZEUS data:
no fixed-target data problems,
like heavy target corrections,
isospin symmetry assumptions…

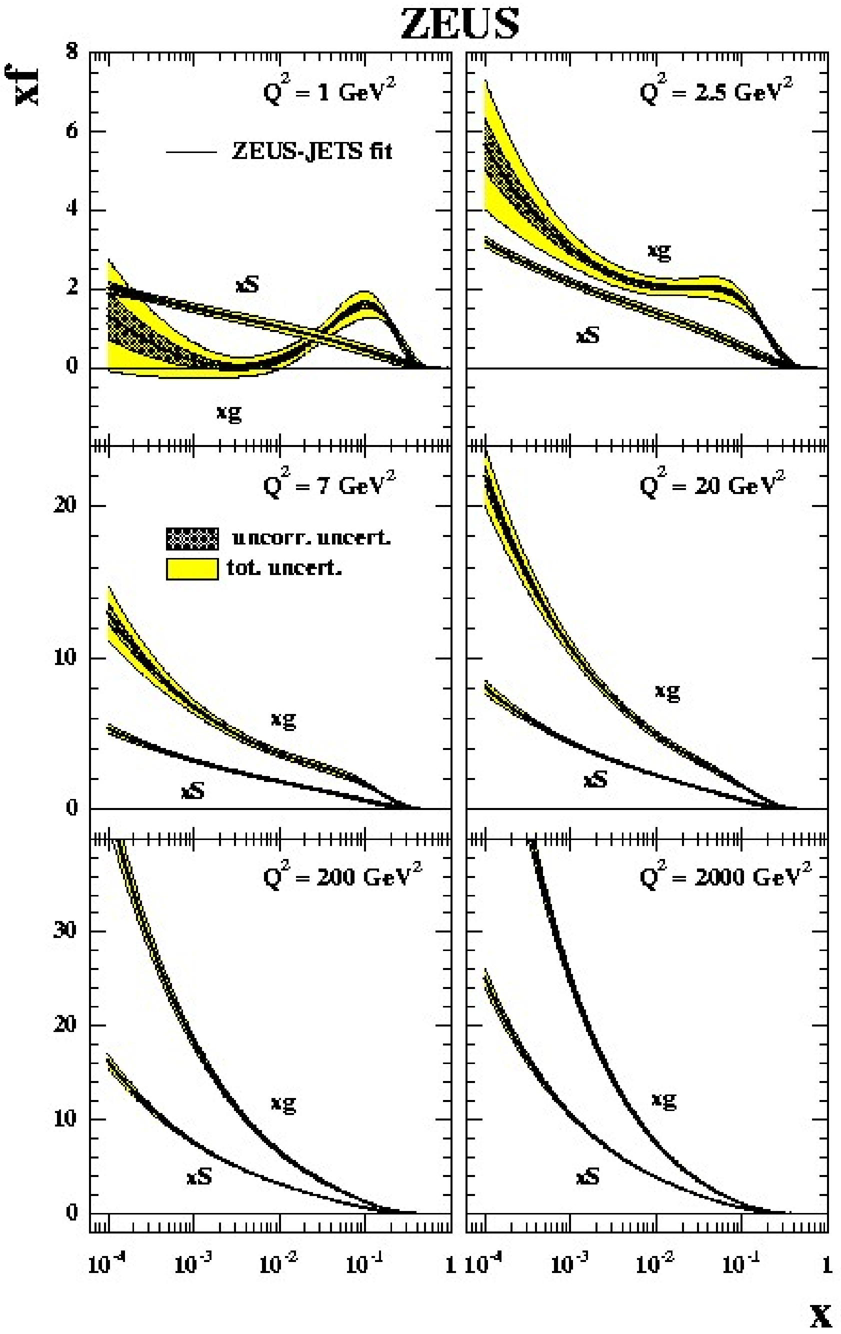


Including Jet data: The ZEUS-JETS NLO-QCD fit

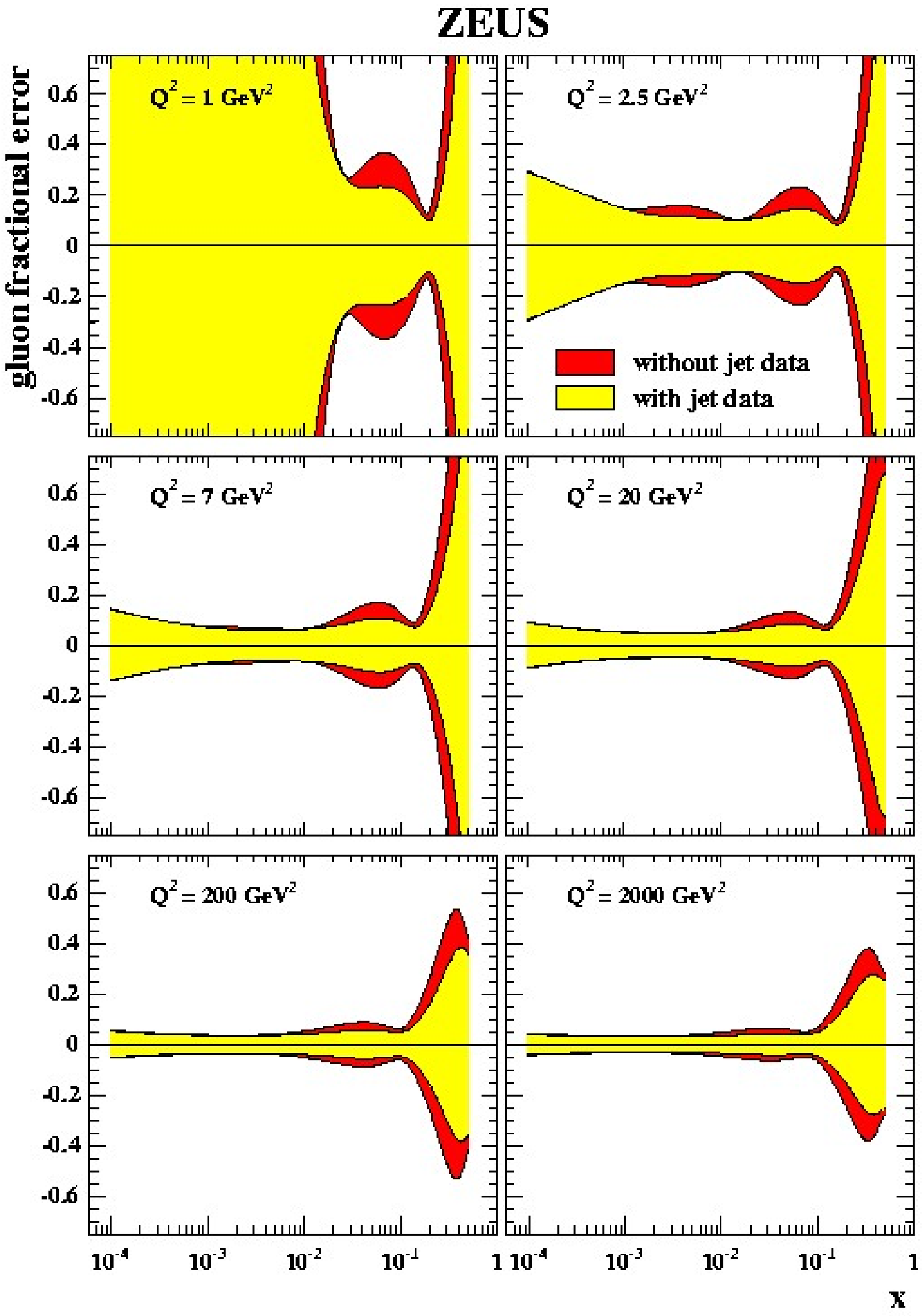


Jet data do improve fit

Gluon at low Q^2 with much reduced errors



Including Jet data:
The ZEUS-JETS NLO-QCD fit



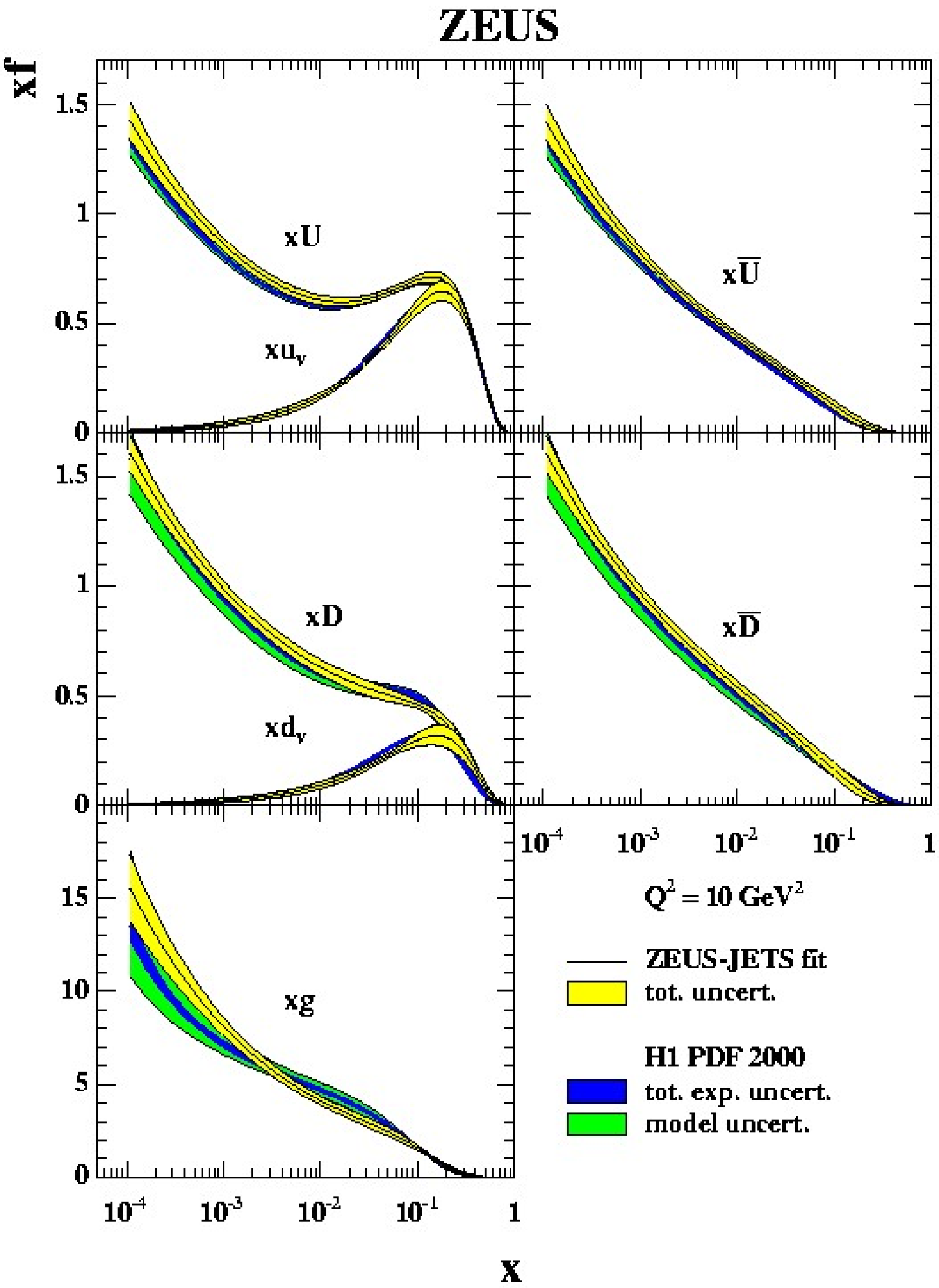
Inclusion of Jet data does not change shape significantly: thus, Jet data and Inclusive data are internally consistent

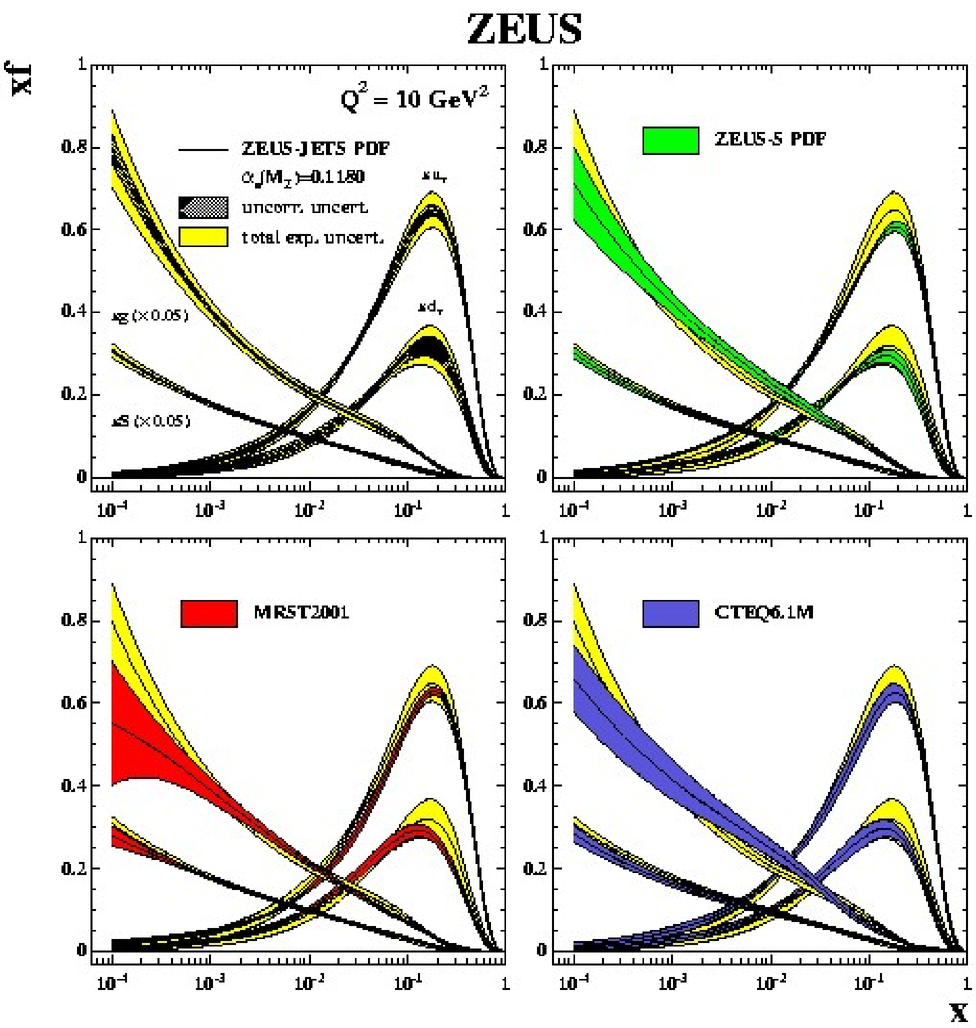
Jet data bring improvement especially in the region 0.01 < x < 0.4

Further improvement in this region only with the HERA II data: greatly increased statistics in the high Q^2 range

Jet data have been used also by MRST and CTEQ, however, not in the rigorous way used here by ZEUS

Including Jet data: The ZEUS-JETS NLO-QCD fit

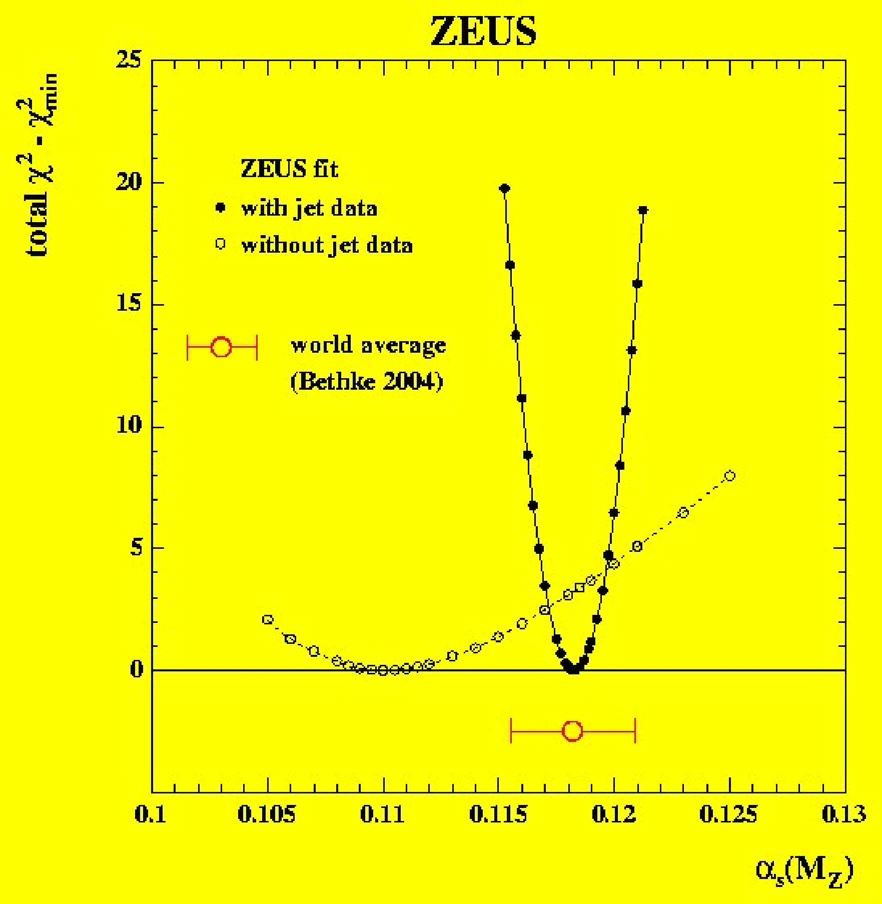




Reasonable agreement:

With H1 PDF2000, MRST2001, CTEQ6

Including Jet data: The ZEUS-JETS NLO-QCD fit



Jet data break the correlation between gluon shape and α_s value

Marked improvement in precision

First NLO extraction of α_s using HERA data alone!

Expect error reduction of 0.0005, if using NNLO

ZEUS $\alpha_s(M_Z^2) = 0.1183 \pm 0.0028(exp) \pm 0.0008(model)$

cf. H1 + BCDMS $\alpha_s(M_Z^2) = 0.1150 \pm 0.0017(exp) {}^{+0.0009}_{-0.0005}(model)$

Both values very close to the fixed values used in ZEUS-S and H1 PDF2000

PART 2:

Accessing the highest x-values

- F_L measurement and extraction
- F_2 at lowest Q^2 values
- F_2 for charm and bottom quarks in the proton