Proton Structure Functions at high Q^2 and high x at HERA

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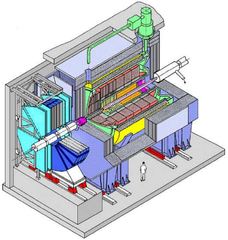
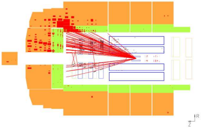
On Behalf of the ZEUS and H1 Collaborations

42nd Recontres de Moriond, QCD and Hadronic Interactions
17 - 24 March, 2007, La Thuile, Italy

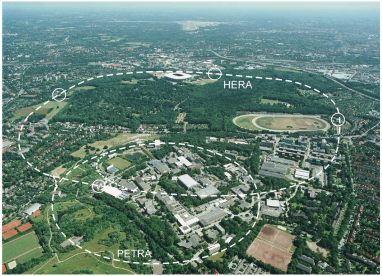
HERA - an ep collider, $\sqrt{s} = 318GeV$

H1

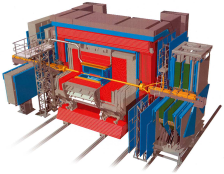


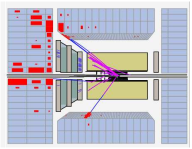


$E_e = 27.6GeV \rightarrow\leftarrow E_p = 920GeV$



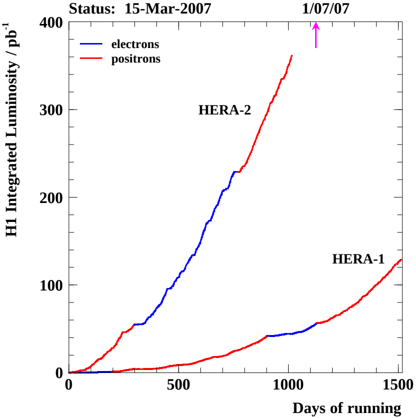
ZEUS

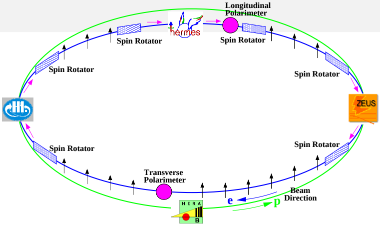




- Compensated Uranium Calorimeter (ZEUS), Liquid Argon Calorimeter (H1)
- Tracking and vertex detectors
- Silicon micro-strip detectors

HERA Operation

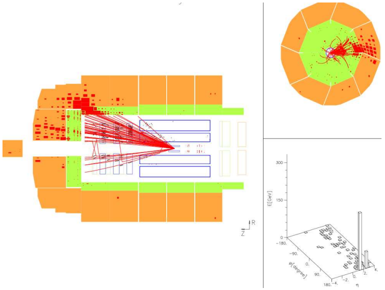




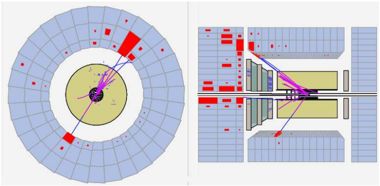
- Longitudinally polarised lepton beams - new for HERA II
- Very successful data taking period recently
- HERA scheduled to shutdown on July 2nd 2007
- The end of a legendary 14 year program

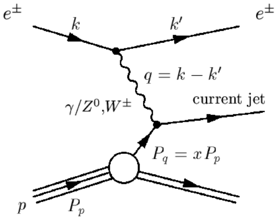
Deep Inelastic Scattering at HERA

H1, CC event



ZEUS, NC event





Q^2: Probing power

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

x: Mom. fraction of struck quark

$$x = \frac{Q^2}{2p\cdot q}$$

y: Energy fraction transferred from lepton in p rest frame

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

NC DIS Cross Sections

$$\frac{d^2\sigma_{NC}(e^\pm p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}[Y_+F_2 \mp Y_-xF_3 - y^2F_L]$$

$$\tilde{\sigma}^{e^\pm p}_{NC} = \frac{xQ^4}{2\pi\alpha^2}\frac{1}{Y_+}\frac{d^2\sigma(e^\pm p)}{dxdQ^2} = F_2 \mp \frac{Y_-}{Y_+}xF_3 - \frac{y^2}{Y_+}F_L$$

- $Y_\pm \equiv 1 \pm (1-y)^2$
- Structure functions F_2, F_L and xF_3
  - F_2: dominant contribution

    $$F_2 \propto \sum(q+\bar{q})$$

    $$F_2 = F_2^\gamma + \frac{Q^2}{Q^2+M_Z^2}F_2^{\gamma Z} + [\frac{Q^2}{Q^2+M_Z^2}]^2 F_2^Z$$
  - xF_3: sensitive at HERA at high Q^2

    $$xF_3 \propto \sum(q-\bar{q})$$

    $$xF_3 = \frac{Q^2}{Q^2+M_Z^2}xF_3^{\gamma Z} + [\frac{Q^2}{Q^2+M_Z^2}]^2 xF_3^Z$$
  - F_L: sensitive at low Q^2 and high y

    $$F_L \propto \alpha_s xg(x,Q^2)$$

    Future measurement: 3 month low energy run this May

CC DIS Cross Sections

$$\frac{d^2\sigma_{CC}(e^-p)}{dxdQ^2} = (1 - P_e)\frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 [u + c + (1-y)^2(\bar{d} + \bar{s})]$$

$$\frac{d^2\sigma_{CC}(e^+p)}{dxdQ^2} = (1 + P_e)\frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 [\bar{u} + \bar{c} + (1-y)^2(d + s)]$$

- Sensitive to *u* and *d* valence quarks
  - Flavour dependent probe of proton structure
- Linear polarisation dependence of CC cross section
  - Chiral nature of the weak force
  - Cross section zero for RH ($P_e = 1$) e- or LH ($P_e = -1$) e+
  - $P_e = \frac{N_{RH} - N_{LH}}{N_{RH} + N_{LH}}$

Structure Functions and Parton Density Functions

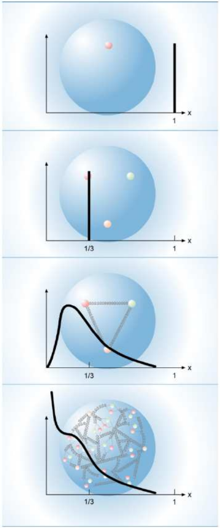
- Theory interprets: SFs = Couplings x PDFs
- PDF = Prob. a quark carries mom. fraction between x and dx
- PDFs not static in QCD
- Structure depends on resolution

A single particle

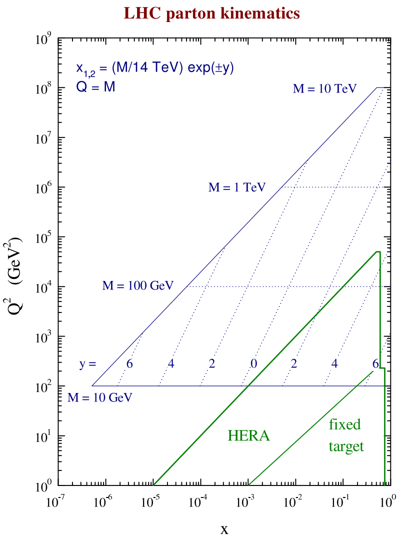
Three valence quarks

Three valence quarks with interactions

Valence and sea quarks with interactions



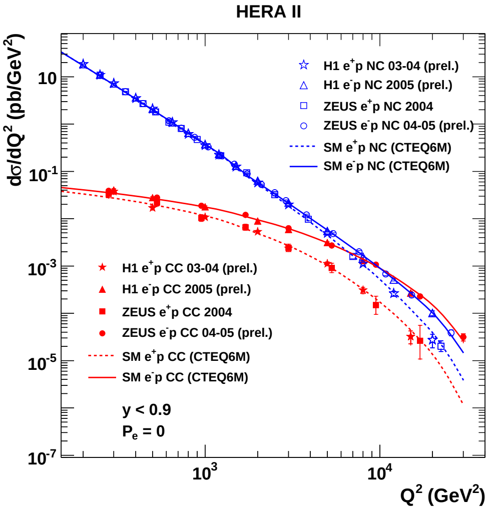
HERA - LHC Kinematic Plane



- DGLAP QCD evolution provides Q^2 dependence but x dependence comes from data
- HERA covers a very important region for the LHC
- Reliable PDFs needed to describe the proton structure

NC & CC Unpolarised Cross Sections

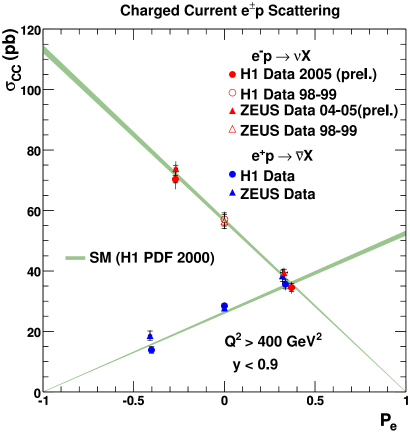
H1 & ZEUS prelim. 2006



- NC cross section dominated by photon exchange
- Sensitive to the massive Z^0 contribution at high Q^2
- EW unification as NC and CC cross sections become similar

CC Polarised Cross Sections

H1prelim-06-041,
ZEUS-prel-06-002



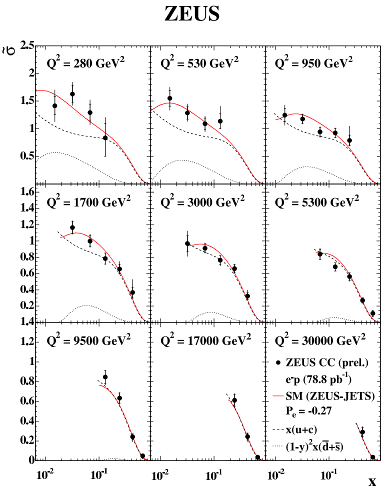
- Linear dependence of CC cross section with lepton polarisation
- $P_e = \frac{N_{RH} - N_{LH}}{N_{RH} + N_{LH}}$
- ZEUS and H1 measurements in good agreement with SM
- $\sigma_{CC}(e^- p)$ extrapolated to $P_e = 1$, prel results:

H1: $-0.9\text{pb} \pm 2.9_{\text{stat}} \pm 1.9_{\text{sys}} \pm 2.9_{\text{pol}}$

ZEUS: $0.8\text{pb} \pm 3.1_{\text{stat}} \pm 5.0_{\text{sys+pol}}$

CC Cross Sections: Flavour Sensitivity

ZEUS-prel-06-002



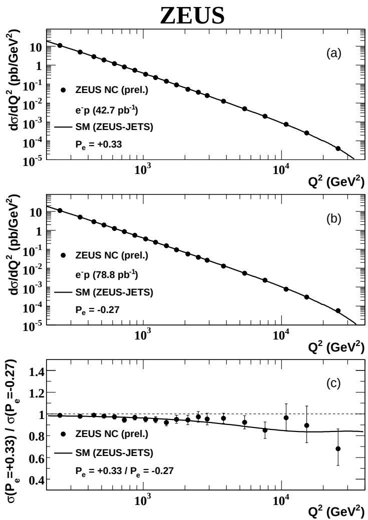
- Flavour selecting nature of CC
- $\tilde{\sigma}_{CC}(e^-p) \propto x[u + c + (1-y)^2(\bar{d} + \bar{s})]$
- Legend:

- - - x(u+c)

···· $(1-y)^2x(\bar{d}+\bar{s})$

NC Polarised Cross Sections

ZEUS-prel-06-001



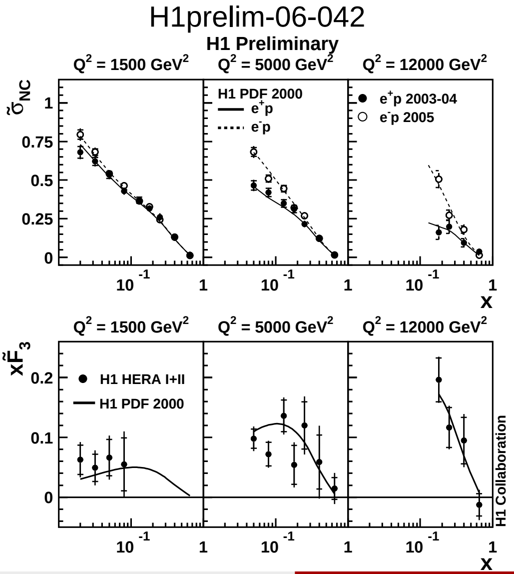
Top, middle, bottom plots:

- $d\sigma/dQ^2$ with +ve P_e (+0.33)
- $d\sigma/dQ^2$ with -ve P_e (-0.27)
- Ratio of cross-sections, +ve P_e / -ve P_e

Polarisation dependence evident at high Q^2

- First observation of parity violation in NC ep scattering at such small distances (10^{-18}m)

xF_3 extraction



- Reduced cross section (ignoring F_L)

$$\tilde{\sigma}^{e^{\pm}p} = F_2 \mp \frac{Y_-}{Y_+} xF_3$$

- Extraction of xF_3

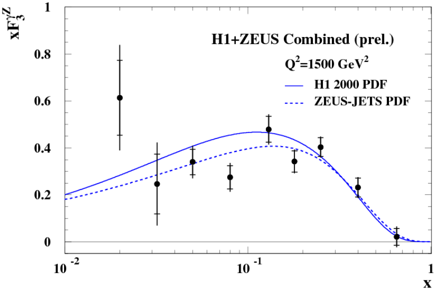
$$\tilde{\sigma}^{e^{-}p} - \tilde{\sigma}^{e^{+}p} = \frac{Y_-}{Y_+} 2xF_3$$

$xF_3 \propto \sum(q - \bar{q})$

Mainly γ/Z interference

$xF_3^{\gamma Z}$ interference structure function

H1prelim-06-142, ZEUS-prel-06-022



$$xF_3 = -a_e \chi_Z xF^{\gamma Z} + 2 v_e a_e \chi_Z^2 xF_3^Z$$

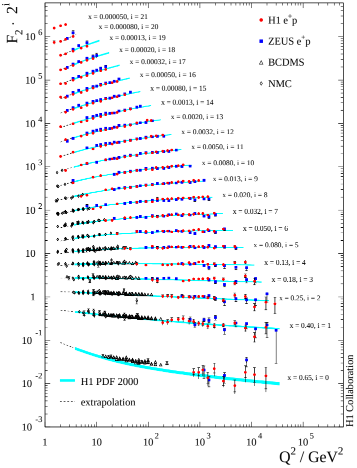
$$xF_3^{\gamma Z} \approx \frac{x}{3}(2u_v + d_v)$$

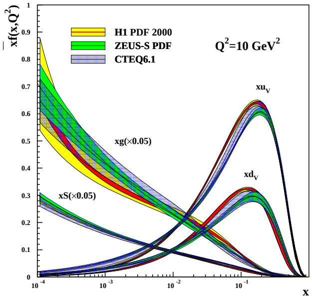
- v_e small, $\chi_Z < 1$, so $xF^{\gamma Z}$ dominates
- Weakly dependent on Q^2, so swim and average to $Q^2 = 1500\,\mathrm{GeV}^2$
- Exploit maximum high Q^2 data by combining H1 and ZEUS results

Structure Functions and PDFs

H1: EPJ C30 (2003) 1

ZEUS: PRD 67 (2005) 012007



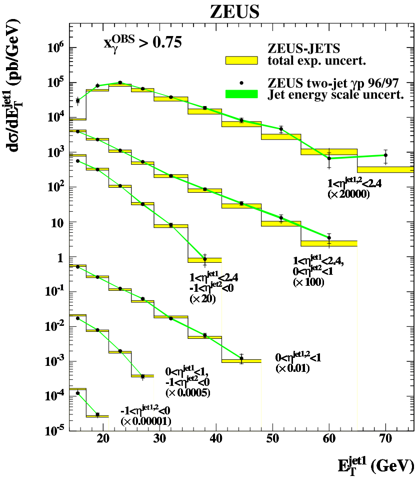


- HERA data well described by NLO pQCD
- Scaling violations described well
  - Low x: $g \to q\bar{q}$
  - High x: $q \to gq$

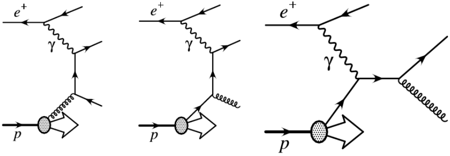
NLO QCD fit including Jets

ZEUS: EPJ C42 (2005) 1

Photoproduction ($Q^2 \sim 0$) dijets



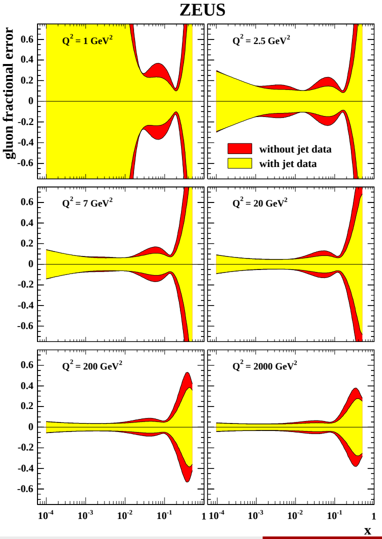
Boson Gluon Fusion, QCD Compt.

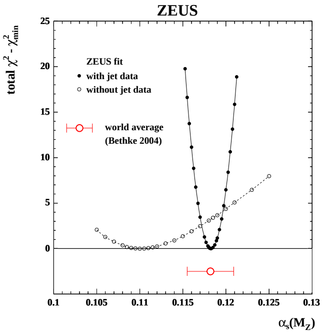


- Jets give access to gluon and α_s
  - Photoproduction ($Q^2 = 0$) dijets
  - DIS inclusive jets
- First fit using just HERA data including jets

Improvement to PDFs Using Jets at HERA

ZEUS: EPJ C42 (2005) 1

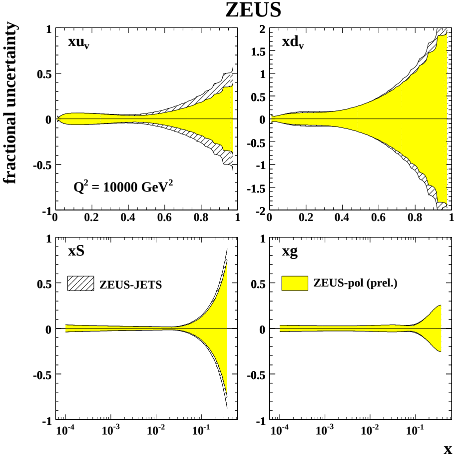




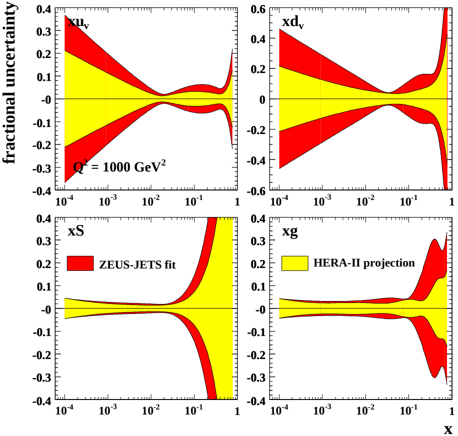
- Jet data help constrain the gluon and α_s
- Red band → without jet data
- Yellow band → with jet data

PDFs Incl. Recent HERA II Data and Total Projected fit

ZEUS-prel-06-003
Incl. prel. HERA II e^-p NC/CC



hep-ex/0507032
Total projected improvement



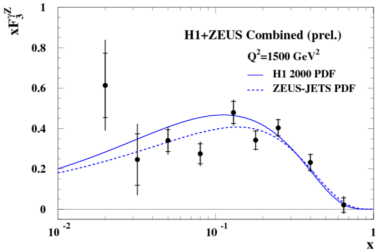
- Already seeing improvements at high-x; in particular xu_v

Summary

- HERA is providing significant improvements to our knowledge of the proton structure
- New HERA II NC and CC cross sections with longitudinally polarised lepton beams
  - H1 and ZEUS measurements agree well with SM
  - Parity violation clearly observed
- Improvement of statistical precision through H1 & ZEUS combination
- New HERA II data already making improvements to PDF uncertainties

- Outlook
  - Entering last few months of HERA operation ☹
  - Analysis of complete HERA data, $\approx 1fb^{-1}$, to come! ☺

$xF_3^{\gamma Z}$ interference structure function



- Sum rule

$$\int_0^1 F_3^{\gamma Z} dx = \int_0^1 (\tfrac{2}{3}u_v + \tfrac{1}{3}d_v) dx = \tfrac{5}{3}$$

- Combined H1 and ZEUS measurement

$$\int_{0.02}^{0.65} F_3^{\gamma Z} dx = 1.21 \pm 0.09(\mathrm{stat}) \pm 0.08(\mathrm{sys})$$

- Consistent with H1 and ZEUS QCD fits

$$\text{H1: } \int_{0.02}^{0.65} F_3^{\gamma Z} dx = 1.12 \pm 0.02$$

$$\text{ZEUS: } \int_{0.02}^{0.65} F_3^{\gamma Z} dx = 1.06 \pm 0.02$$

Using jet data in PDF fits – pioneering paper H1 Eur.Phys.J.C19(2001)289 but for $\alpha_s(M_Z)$ and gluon PDF only

Where does the information come from in a global fit compared to a fit including only ZEUS data ?

	Global	**HERA Only**
Valence	Predominantly fixed target data (ν-Fe and $\mu D/\mu p$)	High Q^2 NC/CC $e^{\pm}$ cross sections
Sea	Low-x from NC DIS High-x from fixed target Flavour from fixed target	Low-x from NC DIS High-x less precise Flavour ?(need assumptions)
Gluon	Low-x from HERA $dF_2/d\ln Q^2$ High-x from Tevatron jets and momentum sum rule	Low-x from HERA $dF_2/d\ln Q^2$ High-x from jet data and momentum sum rule

ANALYSES FROM HERA ONLY …

— Systematics well understood - measurements from our own experiment

—No complications from heavy target Fe or D corrections

—No assumption on strong isospin

Recap of the method

- $xuv(x) = Au\ x^{av}\ (1-x)^{bu}\ (1 + c_u\ x)$
  $xdv(x) = Ad\ x^{av}\ (1-x)^{bd}\ (1 + c_d\ x)$
  $xS(x) = As\ x^{as}\ (1-x)^{bs}\ (1 + c_s\ x)$
  $xg(x) = Ag\ x^{ag}\ (1-x)^{bg}\ (1 + c_g\ x)$
  $x\Delta(x) = x(d-u) = A\Delta\ x^{av}\ (1-x)^{bs+2}$

Parametrize parton distribution functions PDFs at $Q^2_0 = 7\ \mathrm{Gev}^2$ →

Evolve in Q^2 using NLO DGLAP (QCDNUM 16.12) →

$$\frac{\partial \mathbf{q_i}(\mathbf{x},\mathbf{Q^2})}{\partial \log \mathbf{Q^2}} = \frac{\alpha_S}{2\pi}\int_x^1 \frac{\mathbf{dy}}{\mathbf{y}}\Big\{\mathbf{P_{q_iq_j}}(\mathbf{y},\alpha_S)\ \mathbf{q_j}(\frac{\mathbf{x}}{\mathbf{y}},\mathbf{Q^2}) + \mathbf{P_{q_ig}}(\mathbf{y},\alpha_S)\ \mathbf{g}(\frac{\mathbf{x}}{\mathbf{y}},\mathbf{Q^2})\Big\}$$

$$\frac{\partial \mathbf{g}(\mathbf{x},\mathbf{Q^2})}{\partial \log \mathbf{Q^2}} = \frac{\alpha_S}{2\pi}\int_x^1 \frac{\mathbf{dy}}{\mathbf{y}}\Big\{\mathbf{P_{gq_j}}(\mathbf{y},\alpha_S)\ \mathbf{q_j}(\frac{\mathbf{x}}{\mathbf{y}},\mathbf{Q^2}) + \mathbf{P_{gg}}(\mathbf{y},\alpha_S)\ \mathbf{g}(\frac{\mathbf{x}}{\mathbf{y}},\mathbf{Q^2})\Big\}$$

Convolute PDFs with coefficient functions to give structure functions and hence cross-sections →

$$\frac{F_2(x,Q^2)}{x} = \int_0^1 \frac{dy}{y}\Big[\Sigma_i C_2(z,\alpha_s)\,q_i(x,Q^2) + C_g(z,\alpha_s)\,g(y,Q^2)\Big]$$

Coefficient functions incorporate treatment of Heavy Quarks by Thorne-Roberts Variable Flavour Number

Model choices ⇒ Form of parametrization at Q^2_0, value of Q^2_0,, flavour structure of sea, cuts applied, heavy flavour scheme

Fit to data under the cuts,

$W^2 > 20\ \mathrm{GeV}^2$ (to remove higher twist),

$30{,}000 > Q^2 > 2.7\ \mathrm{GeV}^2$ ←Use of NLO DGLAP

$x > 6.3\ 10^{-5}$

The χ2 includes the contribution of correlated systematic errors

$$\chi^2 = \sum_i \frac{[\, F_i^{QCD}(p) - \sum_\lambda s_\lambda \Delta_{i\lambda}^{SYS} - F_i^{MEAS}]^2}{(\sigma_i^{STAT})^2} + \sum s_\lambda^2$$

Where $\Delta_{i\lambda}^{SYS}$ is the correlated error on point **i** due to systematic error source **λ** and s_λ are systematic uncertainty fit parameters of zero mean and unit variance

This has modified the fit prediction by each source of systematic uncertainty

The statistical errors on the fit parameters, p, are evaluated from **Δχ2 = 1,** $s_\lambda=0$

The correlated systematic errors are evaluated by the Offset method –conservative method - $s_\lambda=\pm1$ for each source of systematic error

Now use ZEUS data alone - minimizes data inconsistency (but must consider model dependence carefully)

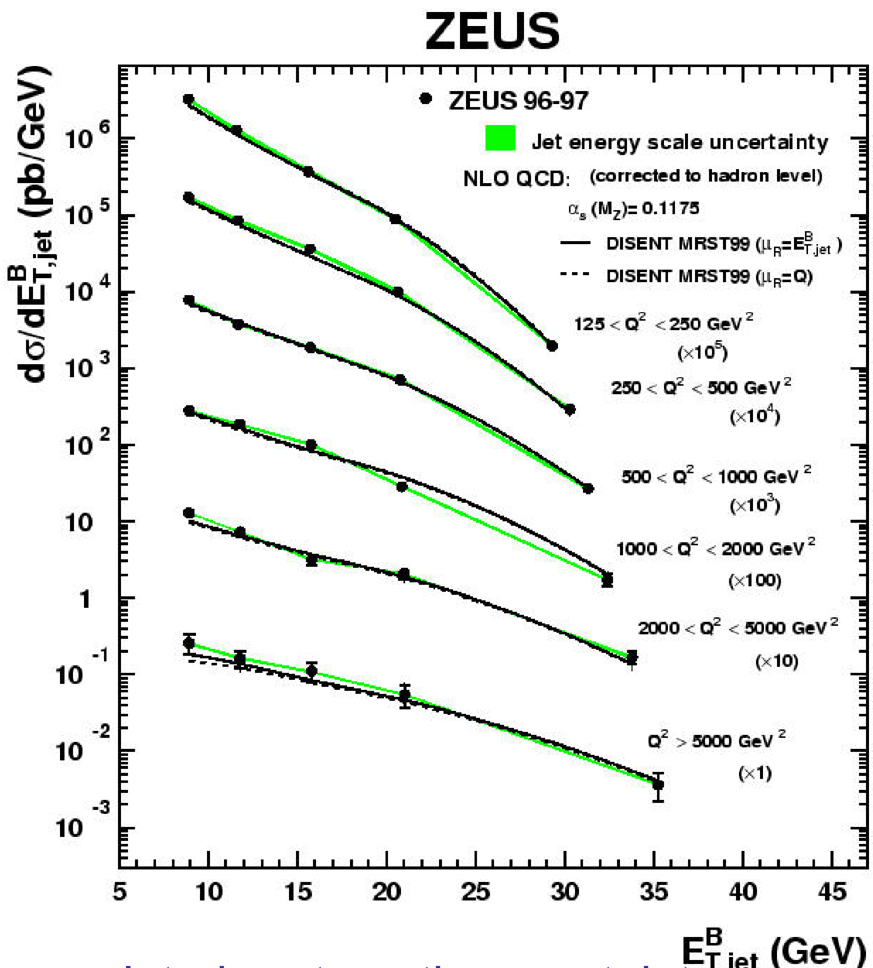
Inclusive Jet Cross Sections in e^+p NC DIS

ZEUS coll., PL B547 164 (2002)

- Phase space:
  $Q^2 > 125\ GeV^2$
  $E^B_{T,jet} > 8$ GeV and $-2 < \eta^B_{jet} < 1.8$
-
- Jets identified with the k_T cluster algorithm in the Breit frame

- Small Experimental uncertainties:
  → jet energy scale (~1% for $E_{T,jet}$>10 GeV)
  => ± 5% on the cross sections

- Small theoretical uncertainties:
  - higher order terms ± 5%
  - Hadronic corrections (C_{had} <10 % and ΔC_{had} ~ 1%)



The calorimeter energy scale is treated as a correlated systematic uncertainty
The factorization scale, μ_F= Q, renormalization scale μ_R=Q, (ET as a cross-check)

Dijet γp cross sections for $x_\gamma^{obs} > 0.75$

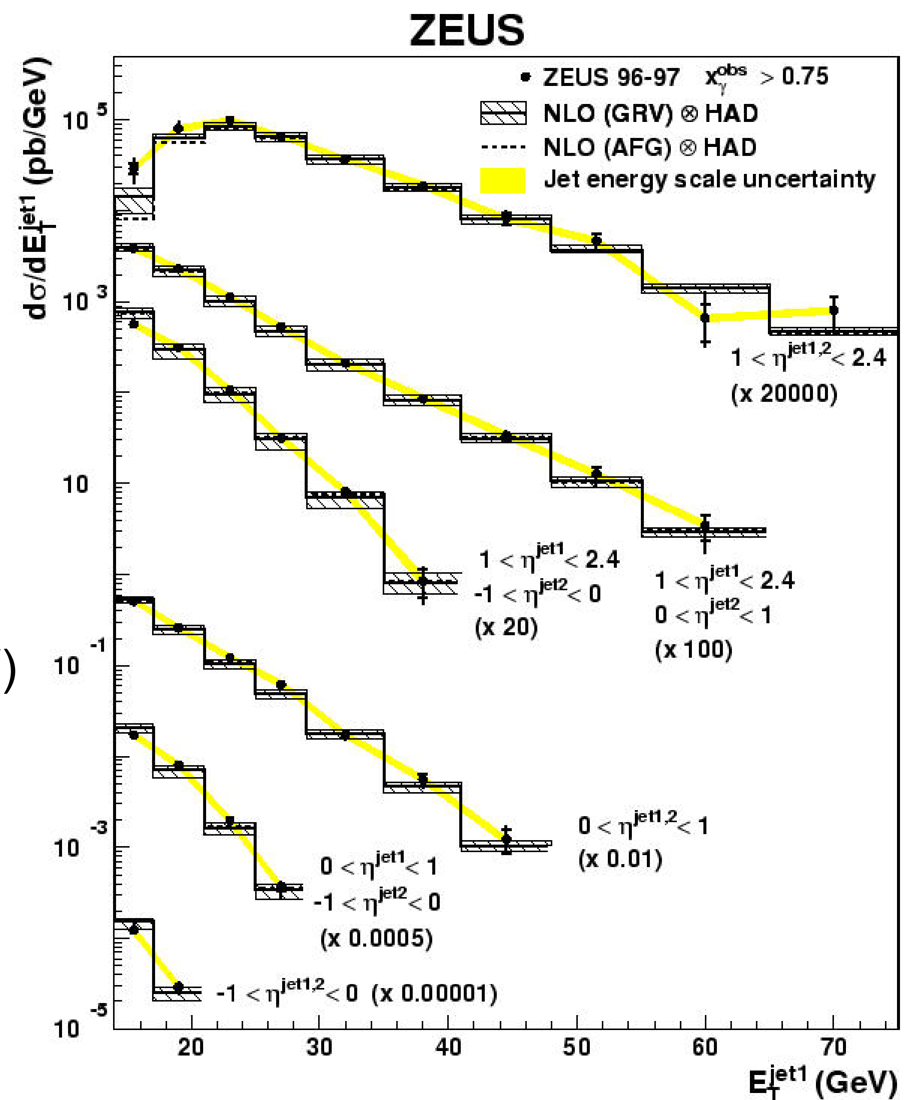
ZEUS Coll., EPJ C23 615 (2002)

- Phase space:
  $E_T^{jet1,(2)} > 14\ (11)$ GeV and
  $-1 < \eta^{jet1,2} < 2.4$ and $x_\gamma^{obs} > 0.75$
  and
  $Q^2 < 1\ GeV^2$ and $134 < W_{\gamma p}^2 < 277\ GeV^2$

- Jets identified with the k_T cluster algorithm in the Lab frame

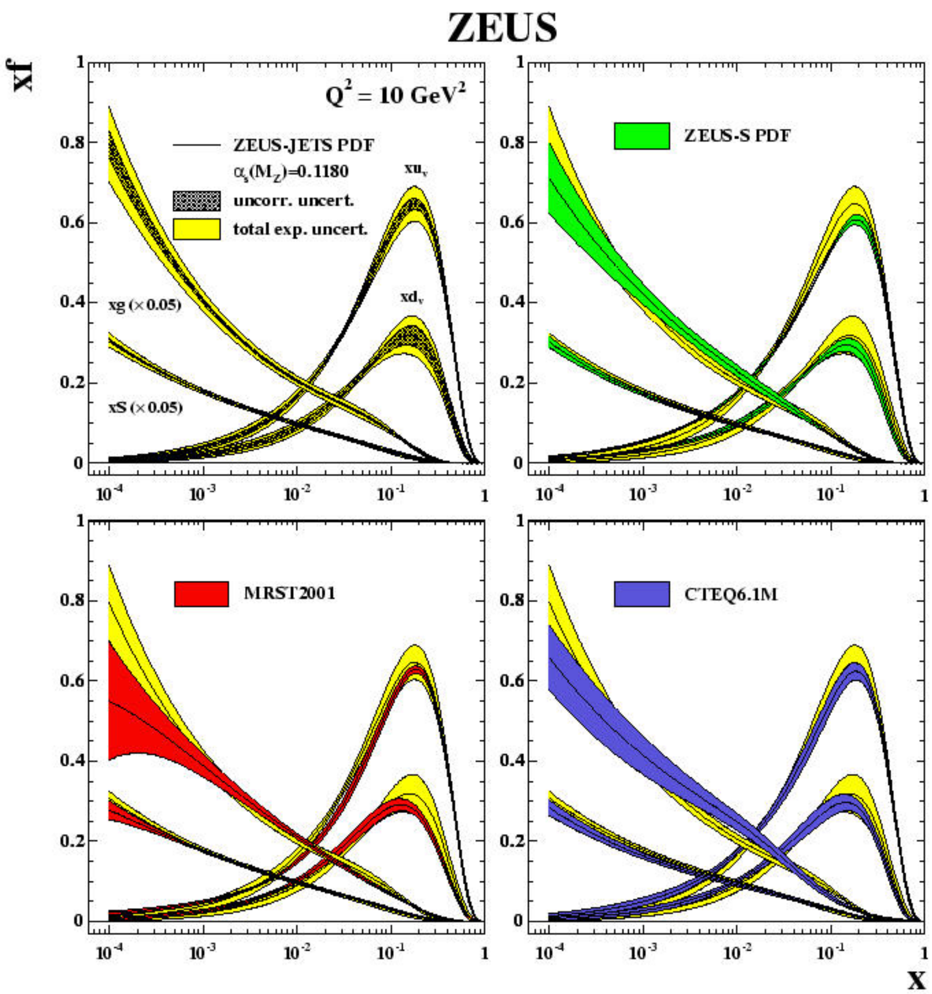
- Small Experimental uncertainties:
  → jet energy scale (~1% for $E_{T,jet}$>10 GeV)
  => ± 5% on the cross sections

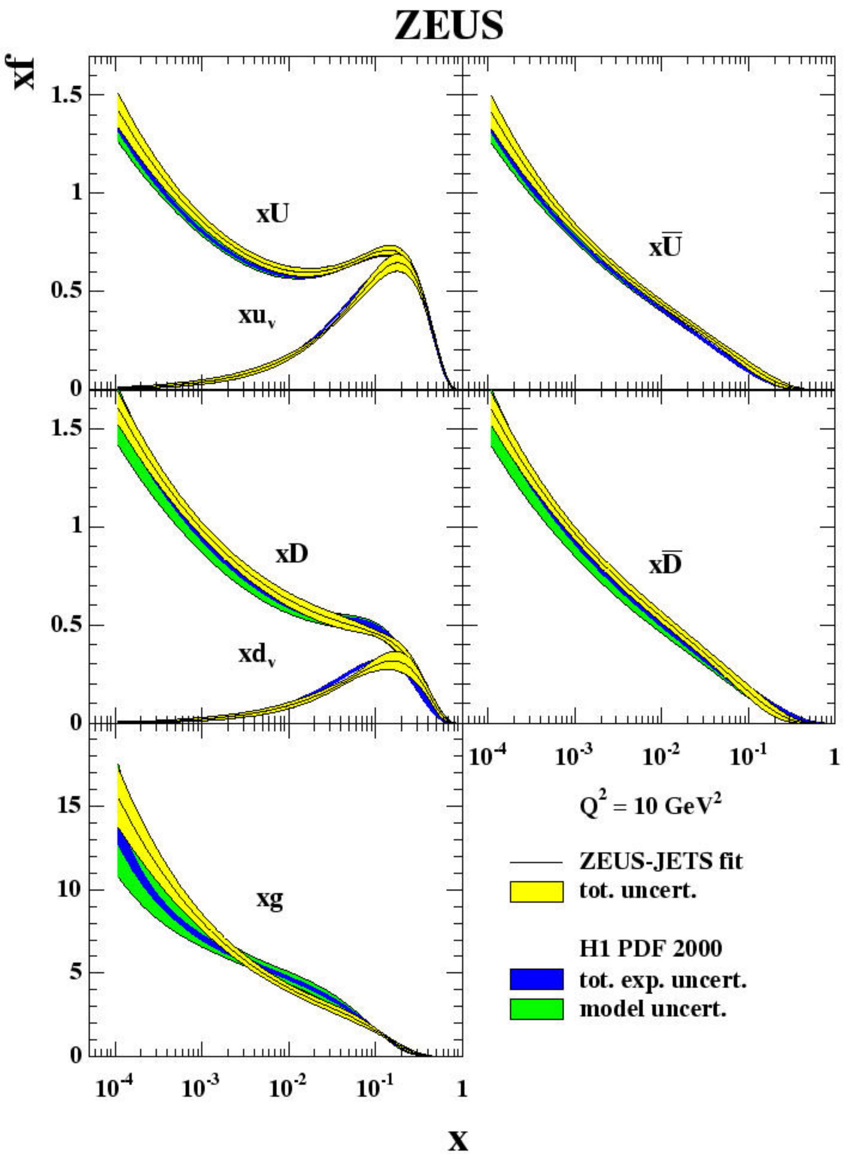
- Small theoretical uncertainties:
  - higher order terms ± 10%
  - Hadronic corrections
  (C_{had} <10 % and ΔC_{had} ~ 2-3%)



The calorimeter energy scale is treated as a correlated systematic uncertainty
The factorization and renormalization scales, $\mu_F = \mu_R = ET/2$ (summed ET of final state particles)

Comparing PDFs





Compatible with ZEUS-S/MRST2001/CTEQ6.1M …and H1

What is the possible impact of HERA –II data on PDF fits ?

- under currently planned running scenarios hep-ph/0509220

Valence	**High Q^2 inclusive NC/CC $e^{\pm}$ cross sections**
Sea	**Low-x from inclusive NC DIS** **High-x ?**
Gluon	**Low-x from HERA $dF_2/dlnQ^2$** **Mid-to-high-x from HERA jet data**

More statistics

More statistics and optimized cross-sections?

Currently ~96 pb^{-1} of e+ p NC and CC data –assume 350 pb^{-1}

Currently ~16 pb^{-1} of e- p NC and CC data – assume 350 pb^{-1}

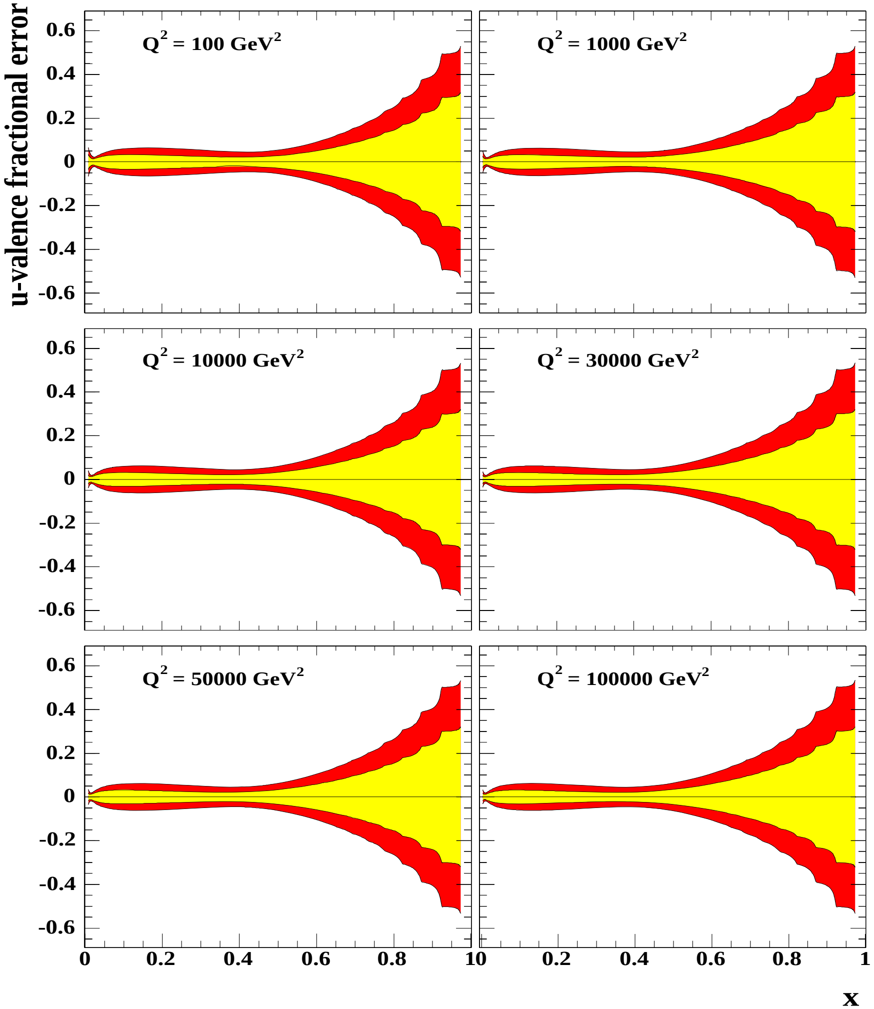
Currently ~37 pb^{-1} of jet data –inclusive DIS and γ-p dijets – assume 500 pb^{-1}

Scale statistical errors from current data- assume systematic errors remain the same

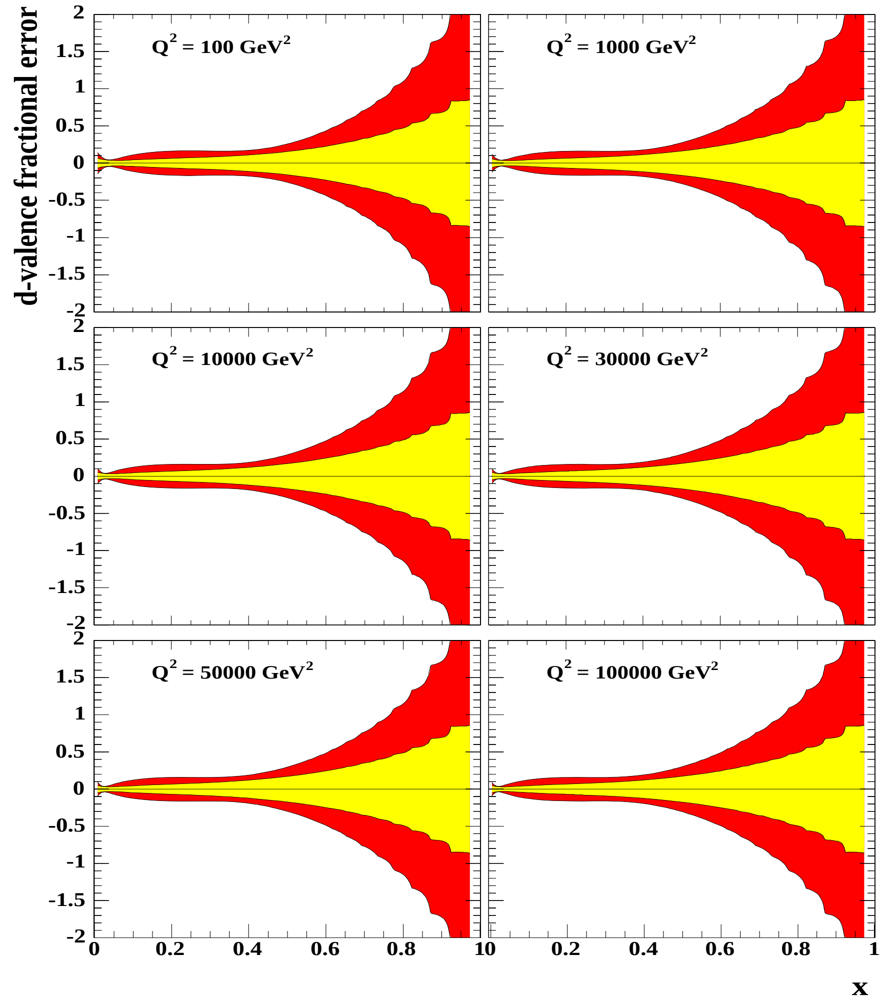
Assume the use of optimised γ-p dijet cross-sections

HERA-II projected fit

u valence



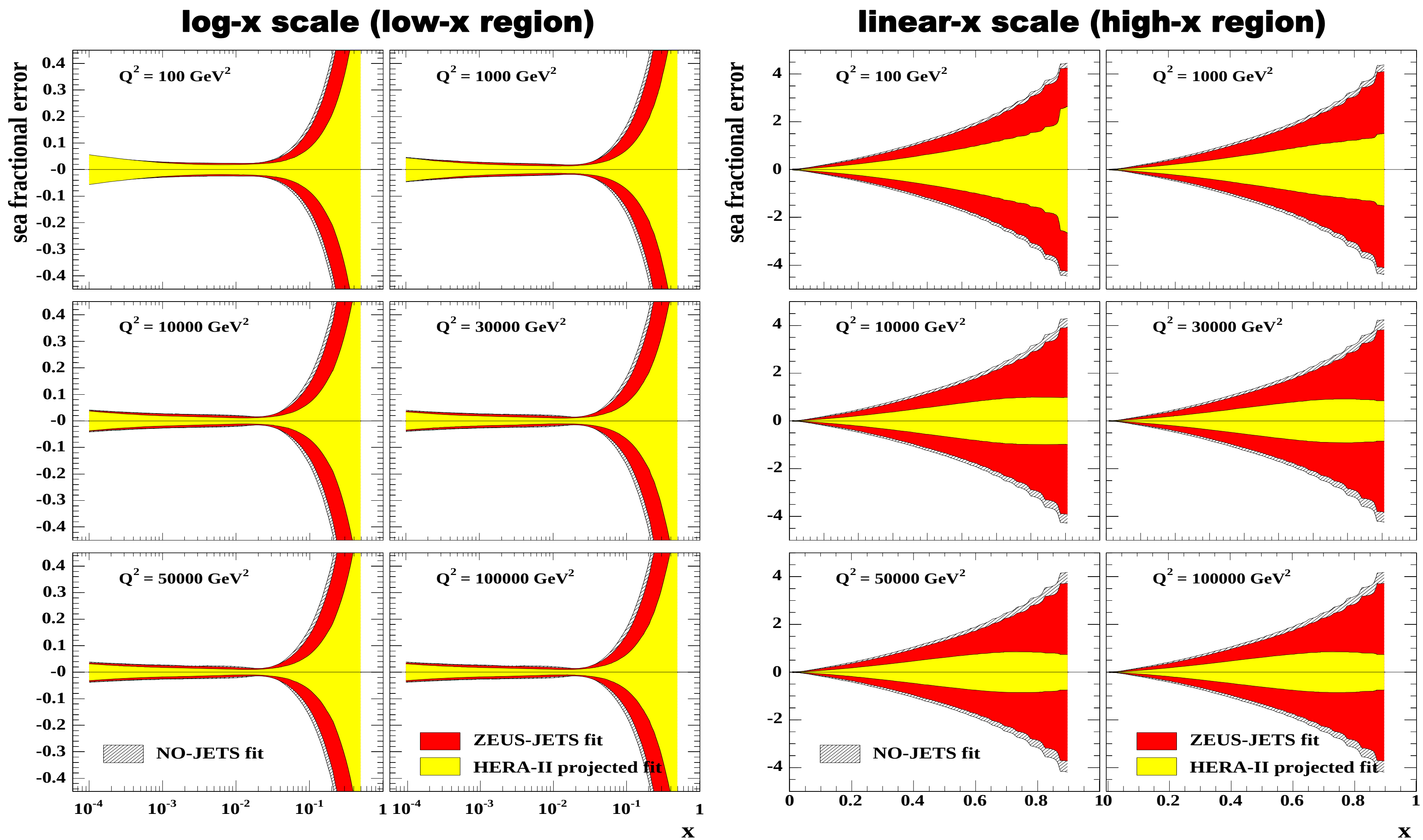
d valence



Fractional uncertainties on u and d valence improved by more statistics

HERA-II projected fit

Sea quark uncertainties

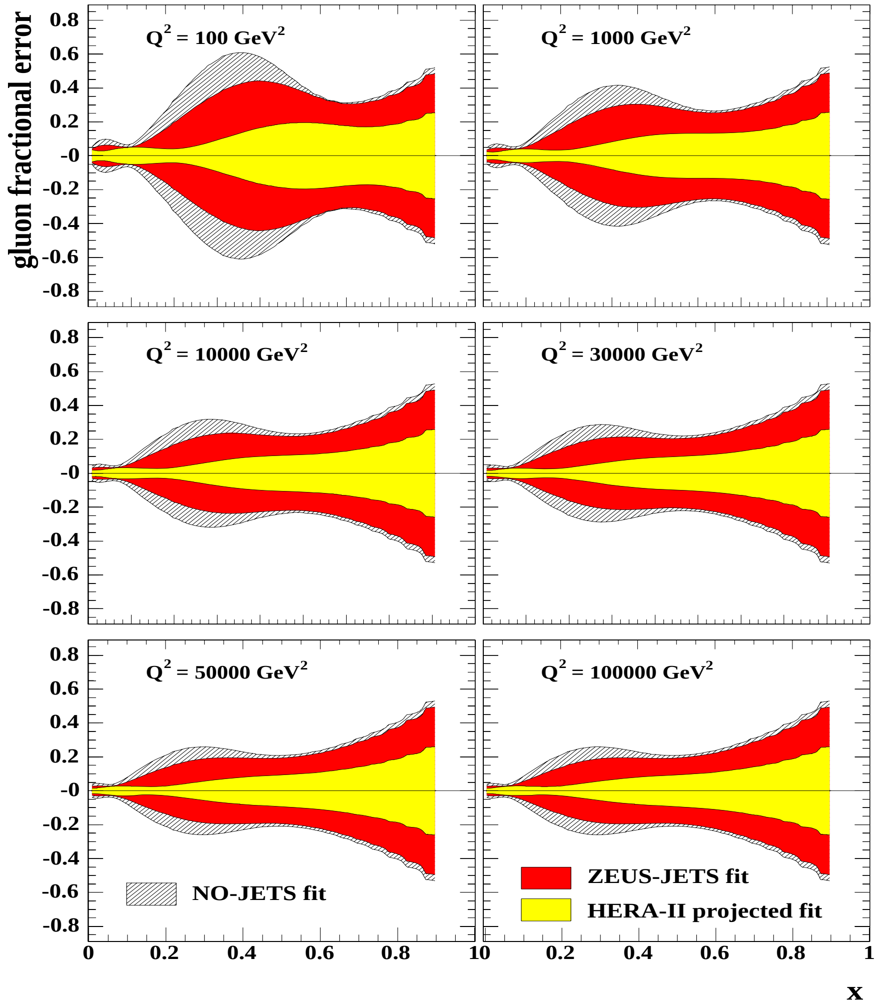


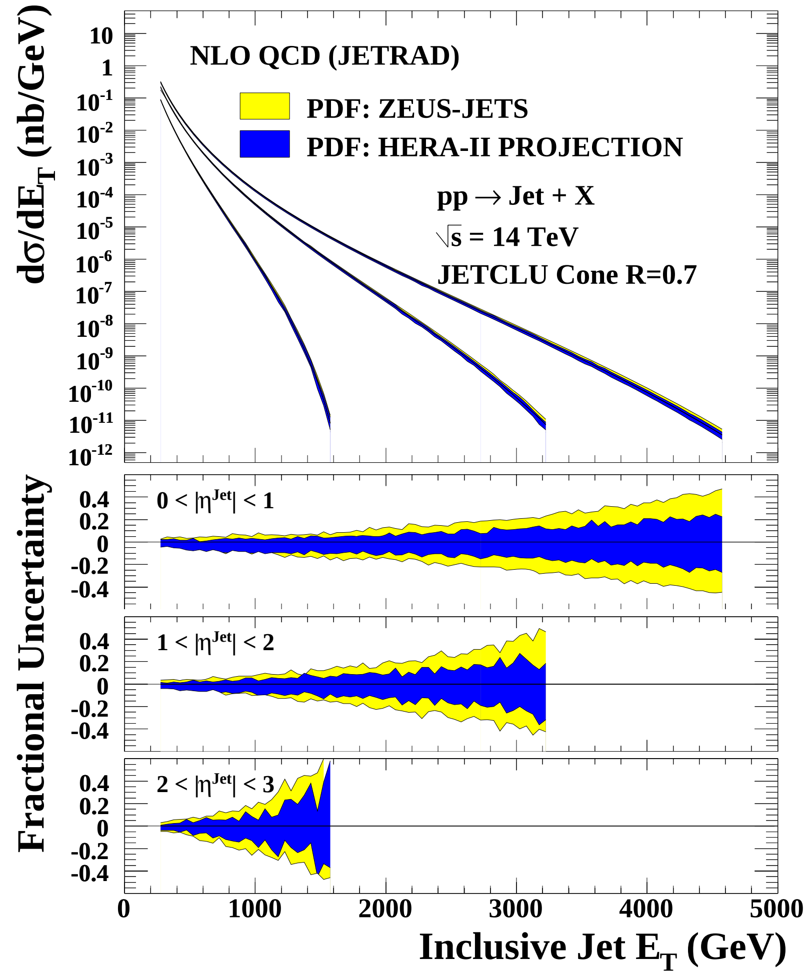
- uncertainties on sea-quark distribution significantly reduced at high-x

HERA-II projected fit

Gluon uncertainties

linear-x scale (high-x region)





Reduced uncertainties on high-x gluon translate into reduced uncertainties on high E_T jet cross-sections at the LHC