# Combined H1-ZEUS Data and the HERA PDFs

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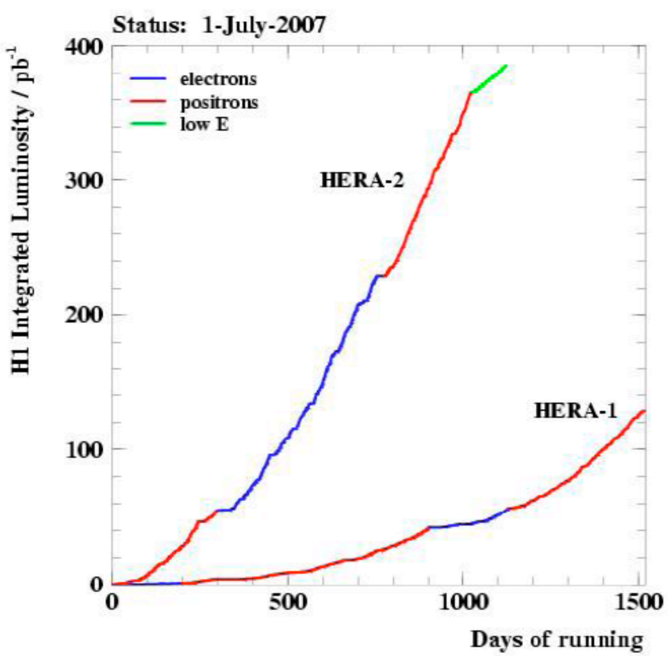
On behalf of the H1 and ZEUS Collaborations

## Outline:

- Introduction
- Combination of H1 and ZEUS DIS data
  - Data/ Method/ Results
- NLO QCD fit to extract HERA PDFs
  - Method/ Model uncertainties/ Results
- Summary

# HERA at DESY

- HERA is an electron-proton collider at DESY, HAMBURG
  - In operation for 15 years until June 2007
- 4 experiments:
  - Fixed Target: HERMES and HERA-B
  - Collider: The H1 and ZEUS
    - general purpose detectors


| | | |
|---|---|---|
| HERA-I | 1992-2000 | Ep=820,920 GeV |
| HERA-II | 2003-2007 | Ep=920,460,575 GeV |

Only HERA-I data is used in this analysis
(~ 115 $pb^{-1}$ of integrated luminosity per experiment)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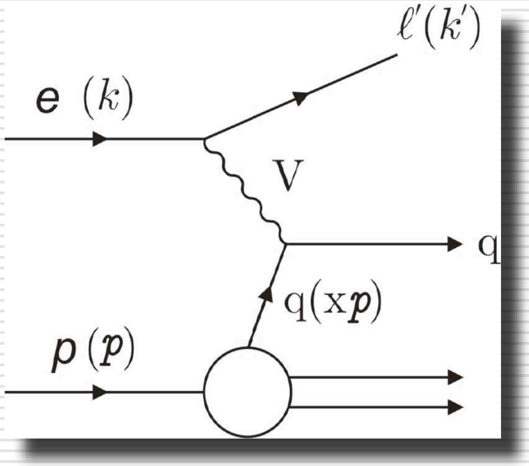
# Deep Inelastic Scattering at HERA




- Kinematic Variables:
  - $Q^2$ : 4-momentum transfer $Q^2 = -q^2 = -(k-k')^2$
  - x Bjorken scaling variable $x = \frac{Q^2}{2p \cdot q}$
  - y: inelasticity $y = \frac{p \cdot q}{p \cdot k}$
  - s: centre-of-mass energy $s = (k+p)^2$
    - The variables are related via: $Q^2 = sxy$

- Neutral Current (NC) : V= $\gamma$ or $Z^0$
- Charged Current (CC): V= $W^\pm$

- The reduced differential cross section for the NC process:

$$\sigma_r(x,Q^2) = \frac{d^2\sigma(e^\pm p)}{dxdQ^2}\frac{Q^4 x}{2\pi\alpha^2 Y_+} = F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2) \mp \frac{Y_-}{Y_+}xF_3(x,Q^2)$$

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

- $F_2$ - dominates: sensitive to sea and valence
- $F_L$ - contributes at high y: sensitive to gluon
- $xF_3$ - contributes at high $Q^2$: sensitive to valence

# Combination of H1 & ZEUS data - Motivation

- Main goal is to know the structure of the proton with highest possible precision

- The purpose of combining the H1 and ZEUS data is to produce a consistent and more precise cross section measurements which are further used for the extractions of parton distribution functions (PDFs)
  - A new model-independent averaging method is used with a coherent treatment of the systematic uncertainties [A.Glazov DIS05]
    - Experiments “cross-calibrate” each other ➔ significant error reduction

- This new precise data is used within NLO QCD framework to extract PDFs with higher accuracy

# Data used for Combination of H1 & ZEUS

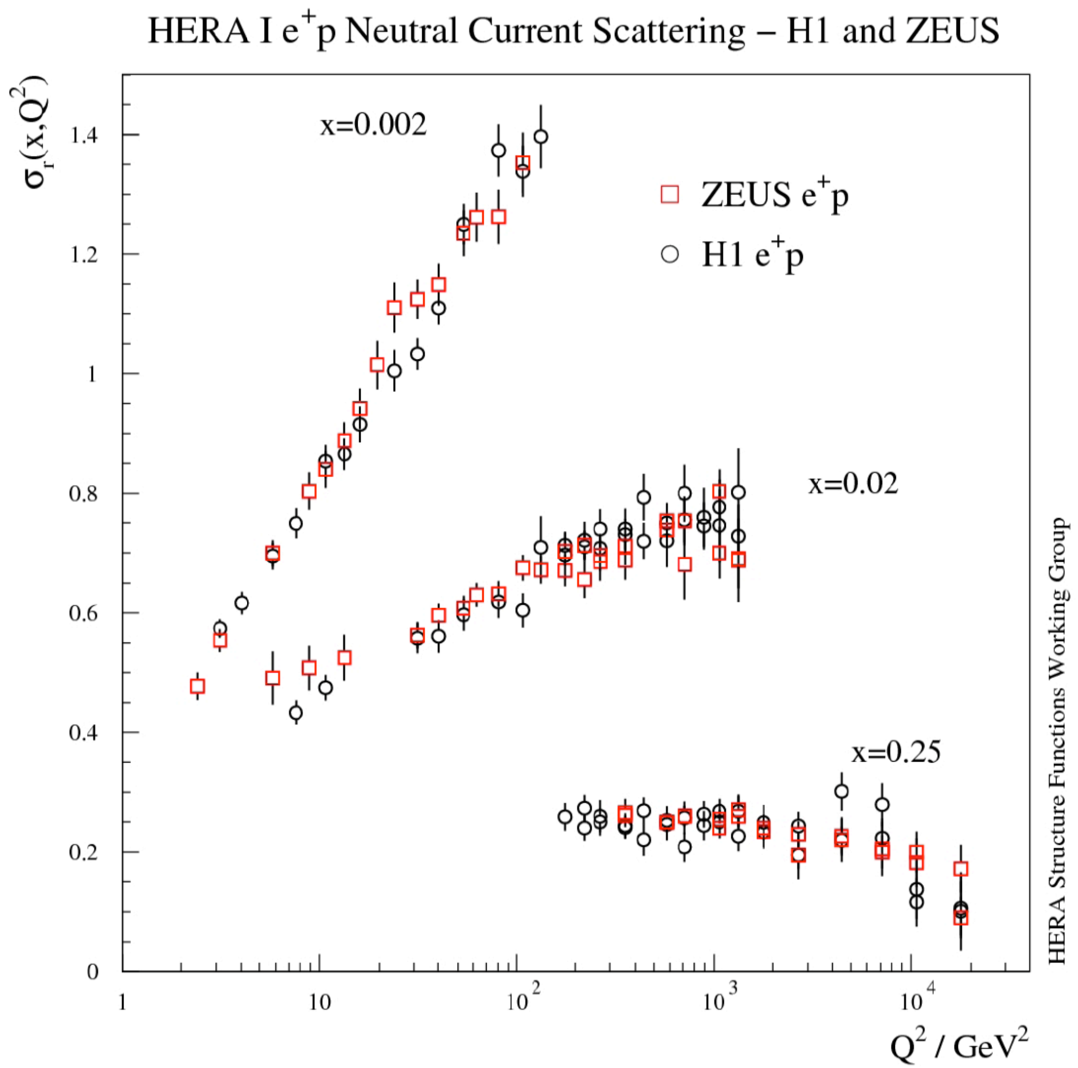
- Published HERA-I inclusive NC and CC DIS data (1994-2000)
  - Ep = 820 (√ s=301) and 920 (√ s=319) GeV, L = 240 $pb^{-1}$
- Kinematic coverage: 1.5<$Q^2$<30000 $GeV^2$ and 0.00006<x<0.65

| data set | | $x$ range | | $Q^2$ range ($GeV^2$) | | $\mathcal{L}$ $pb^{-1}$ | comment |
|---|---|---|---|---|---|---|---|
| H1 NC min. bias | 97 | 0.00008 | 0.02 | 3.5 | 12 | 1.8 | $e^+p$ $\sqrt{s} = 301$ GeV |
| H1 NC low $Q^2$ | 96 – 97 | 0.000161 | 0.20 | 12 | 150 | 17.9 | $e^+p$ $\sqrt{s} = 301$ GeV |
| H1 NC | 94 – 97 | 0.0032 | 0.65 | 150 | 30 000 | 35.6 | $e^+p$ $\sqrt{s} = 301$ GeV |
| H1 CC | 94 – 97 | 0.013 | 0.40 | 300 | 15 000 | 35.6 | $e^+p$ $\sqrt{s} = 301$ GeV |
| H1 NC | 98 – 99 | 0.0032 | 0.65 | 150 | 30 000 | 16.4 | $e^-p$ $\sqrt{s} = 319$ GeV |
| H1 CC | 98 – 99 | 0.013 | 0.40 | 300 | 15 000 | 16.4 | $e^-p$ $\sqrt{s} = 319$ GeV |
| H1 NC | 99 – 00 | 0.00131 | 0.65 | 100 | 30 000 | 65.2 | $e^+p$ $\sqrt{s} = 319$ GeV |
| H1 CC | 99 – 00 | 0.013 | 0.40 | 300 | 15 000 | 65.2 | $e^+p$ $\sqrt{s} = 319$ GeV |
| ZEUS NC | 96 – 97 | 0.00006 | 0.65 | 2.7 | 30 000 | 30.0 | $e^+p$ $\sqrt{s} = 301$ GeV |
| ZEUS CC | 94 – 97 | 0.015 | 0.42 | 280 | 17 000 | 47.7 | $e^+p$ $\sqrt{s} = 301$ GeV |
| ZEUS NC | 98 – 99 | 0.005 | 0.65 | 200 | 30 000 | 15.9 | $e^-p$ $\sqrt{s} = 319$ GeV |
| ZEUS CC | 98 – 99 | 0.015 | 0.42 | 280 | 30 000 | 16.4 | $e^-p$ $\sqrt{s} = 319$ GeV |
| ZEUS NC | 99 – 00 | 0.005 | 0.65 | 200 | 30 000 | 63.2 | $e^+p$ $\sqrt{s} = 319$ GeV |
| ZEUS CC | 99 – 00 | 0.008 | 0.42 | 280 | 17 000 | 60.9 | $e^+p$ $\sqrt{s} = 319$ GeV |

# Cross sections prior combination

- H1 and ZEUS published precise measurements of the NC and CC DIS cross sections
  - For $Q^2<100$ GeV$^2$:
    - Stat error <1%
    - Sys error <3%
  - For $Q^2>1000$ GeV$^2$:
    - Stat error > Sys error

- Plot shows NC reduced cross sections for ZEUS [red] and H1 [black] for selected x bins



# Averaging Method (I)

- The only assumption: H1 and ZEUS measure the same cross-sections at the same kinematic points.
- Prior Combination:
  - Move to a common grid in ($x$,$Q^2$): H1 $x$, ZEUS $Q^2$
    - Using H1PDF 2000

      (checked against the ZEUS-Jets PDFs: very good agreement)
  - Move to 920 GeV $E_p$ beam energy:
    - Using H1PDF 2000
    - Correction sizeable at large y: up to 5% for few points

# Averaging Method (II) - $\chi^2$

- Data is combined using model-independent Hessian fit, in which correlated systematic uncertainties are floated coherently:

$$\chi^2_{\rm exp}\left(M^{i,\rm true},\alpha_j\right)=\sum_i \frac{\left[M^{i,\rm true}-\left(M^i+\sum_j \frac{\partial M^i}{\partial\alpha_j}\alpha_j\right)\right]^2}{\delta_i^2}+\sum_j\frac{\alpha_j^2}{\delta_{\alpha_j}^2}$$

  - $M^i$ - measured cross sections at $(x,Q^2)$
  - $\delta_i$ - statistical and uncorrelated systematic uncertainty
  - $\alpha_j$ - sources of the correlated systematic uncertainties
  - $\delta_{\alpha_j}$ - correlated systematic uncertainty
  - $\frac{\partial M^i}{\partial\alpha_j}$ - sensitivity of data point *i* to the systematic source *j*
  - $M^{i,true}$ - true value we determine

  - By construction: $\chi^2 = 0$ for $M^{i,true} = M^i \;\&\; \alpha_j = 0$
- The $\chi^2$ definition true if uncertainties are absolute (additive)
  - For relative (multiplicative) errors there is a bias: smaller $M^i$ will have smaller relative errors and hence smaller $\chi^2$
    - modify $\chi^2$ definition: translate relative errors to the absolute $\delta_i \longrightarrow \frac{M^{i,true}}{M^i}\delta_i$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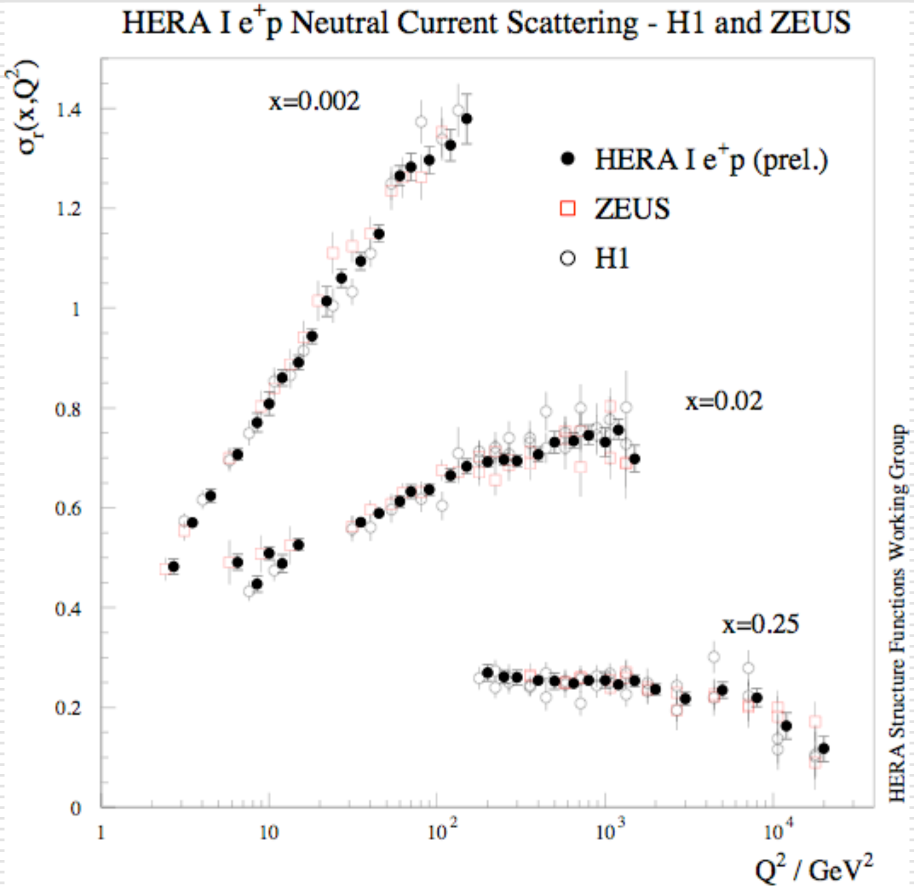
# Uncertainties

- Uncorrelated uncertainties:
  - Statistical errors
  - Poin-to-point uncorrelated systematic uncertainties:
    - e.g statistical errors due to MC simulations
    - Are added in quadrature to the statistical errors
- Correlated uncertainties:
  - Point-to-point correlated systematic uncertainties
    - e.g. electromagnetic and hadronic energy scales calibration
    - Often common for CC and NC for a given experiment and run period
- Overall normalisation uncertainty
  - Correlated for all data points for a given experiment and run period
- Correlations between H1 and ZEUS:
  - H1 and ZEUS use similar analyses methods
  - 12 sources are identified, largest from photo-production MC and hadronic energy scales - procedural errors

# Results

- 1153 individual NC and CC data are averaged to 573 unique cross section points ($\chi^2$ =510)
  - 43 systematic sources from separate experiments and 4 from the combining procedure
- All uncertainties lie within 1$\sigma$ of the published central values, except H1 NC low Q2 96-97- shifted up by 1.6 $\sigma$
- Overall precision improved:
  - $Q^2$<12 GeV$^2$: <2% precision
  - $Q^2$~100 GeV$^2$: 1.5% precision
  - For highest Q2: 10% precision benefiting from increased statistics
- Most significant improvements
  - H1 backward calo energy scale (x3)
  - ZEUS forward energy flow modeling (x4)

## NC $e^+p$ at fixed x



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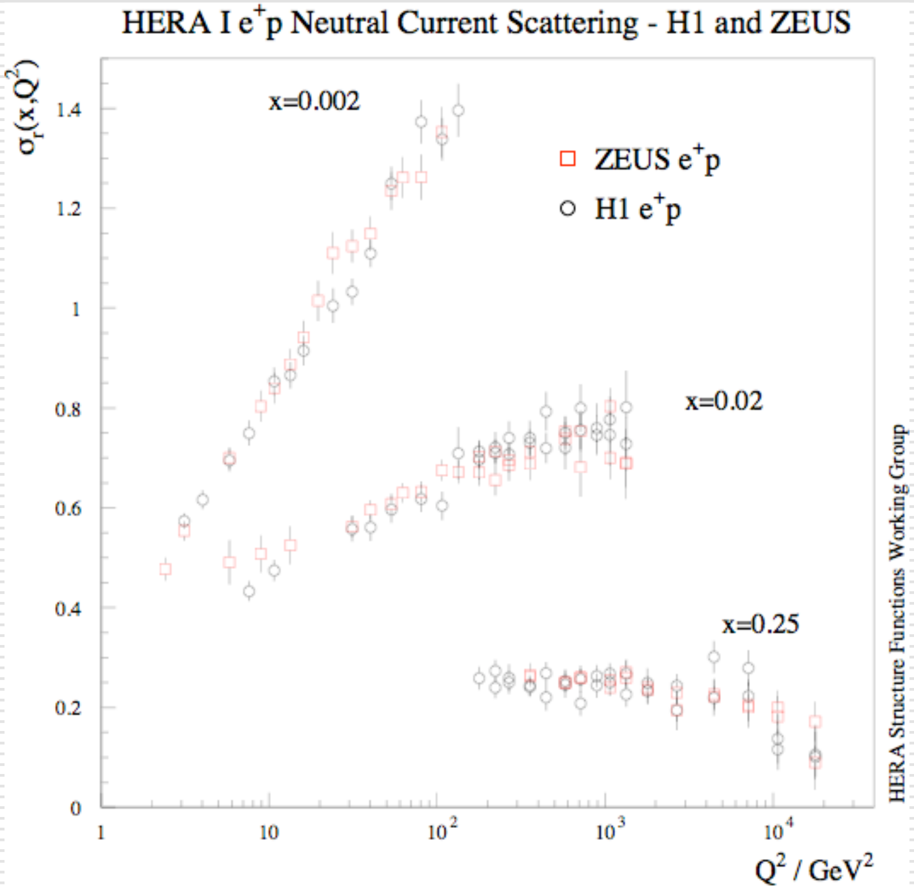

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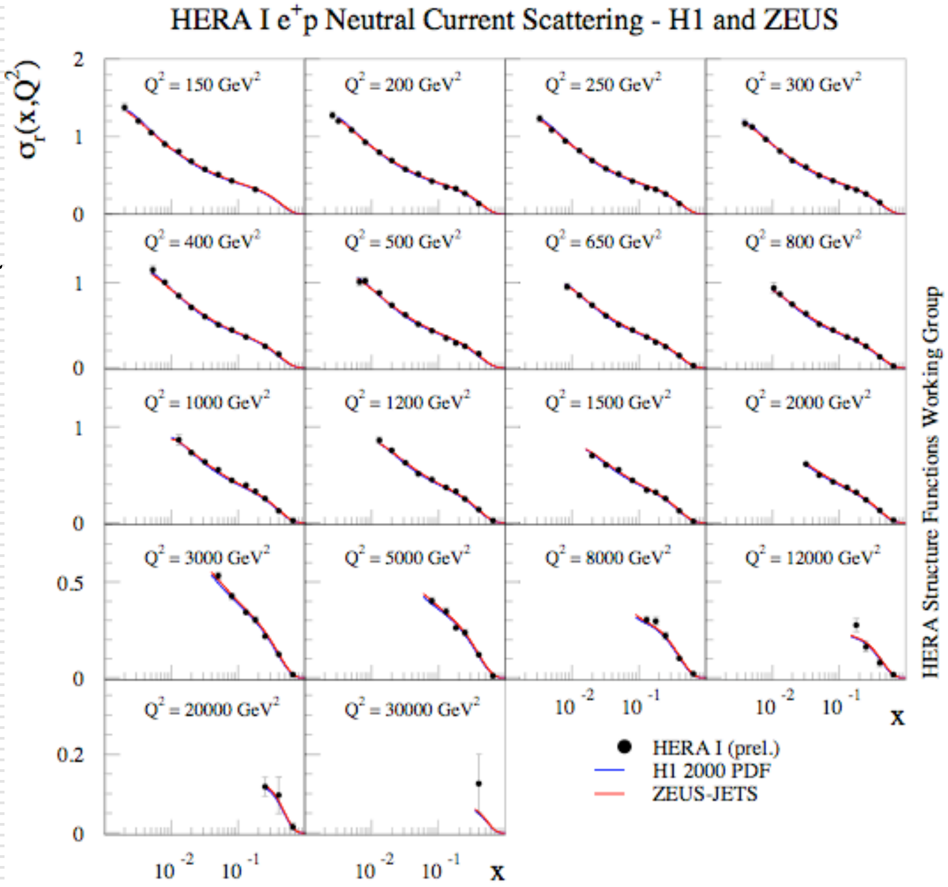
- Most significant improvements
  - H1 backward calo energy scale (x3)
  - ZEUS forward energy flow modeling (x4)
- H1PDF 2000 and ZEUS-Jets PDFs describe well the combined data

## NC $e^+p$ at high $Q^2$



# QCD Analysis

- Context
  - Previously, H1 and ZEUS released their separate sets of PDFs - H1PDF 2000 and ZEUS-Jets - using as sole input their NC and CC inclusive measurements:
    - Results comparable, but there is difference in the gluon shape
  - New combined precise HERA-I data can be used as sole input in a common QCD analysis to extract HERA PDF set
    - first release version is labeled HERAPDF0.1

# HERA PDF parametrisation

- The HERA PDFs combines the best features of H1 and ZEUS for the parametrisation form and choice of partons to be fit
- A generic functional form has been considered:

$$xf(x, Q_0^2) = Ax^B(1-x)^C(1 + Dx + Ex^2 + Fx^3)$$

  - This is used to parametrise the following PDFs:

$$xu_v,\ xd_v,\ x\bar{U} = x\bar{u} + x\bar{c},\ x\bar{D} = x\bar{d} + x\bar{s} + \bar{b}, xg$$

    with the sea flavour break-up at $Q^2_0$ and $f_c$=0.15, $f_s$=0.33

$$s = f_s D,\ c = f_c U$$

  - The number of parameters are chosen by saturation of the $\chi^2$ (i.e. only parameters that bring significant contribution to $\chi^2$ are let to vary)

| PDF | A | B | C | D | E |
|---|---|---|---|---|---|
| xg | Sum rule | FIT | FIT | | |
| $xu_v$ | Sum rule | FIT | FIT | FIT | FIT |
| $xd_v$ | Sum rule | $=B(xu_v)$ | FIT | | |
| $x\bar{U}$ | $\lim_{x\to 0} \bar{U}/\bar{D} \to 1$ | FIT | FIT | | |
| $x\bar{D}$ | FIT | $=B(x\bar{U})$ | FIT | | |

  - This results in 11 free parameters (denoted with FIT in the table)

# QCD Analysis details

- NLO predictions using DGLAP evolution equations
- The input scale $Q^2_0$ = 4 $GeV^2$
- Calculations in Zero-mass variable-number flavour scheme
- Renormalisation and Factorisation scales set to the $Q^2$
- The choices for heavy quark masses: Mc=1.4 GeV, Mb=4.75 GeV
- The strong coupling $\alpha_s$ = 0.1176 [PDG 2006]
- Minimum $Q^2$ = 3.5 $GeV^2$

# Uncertainties

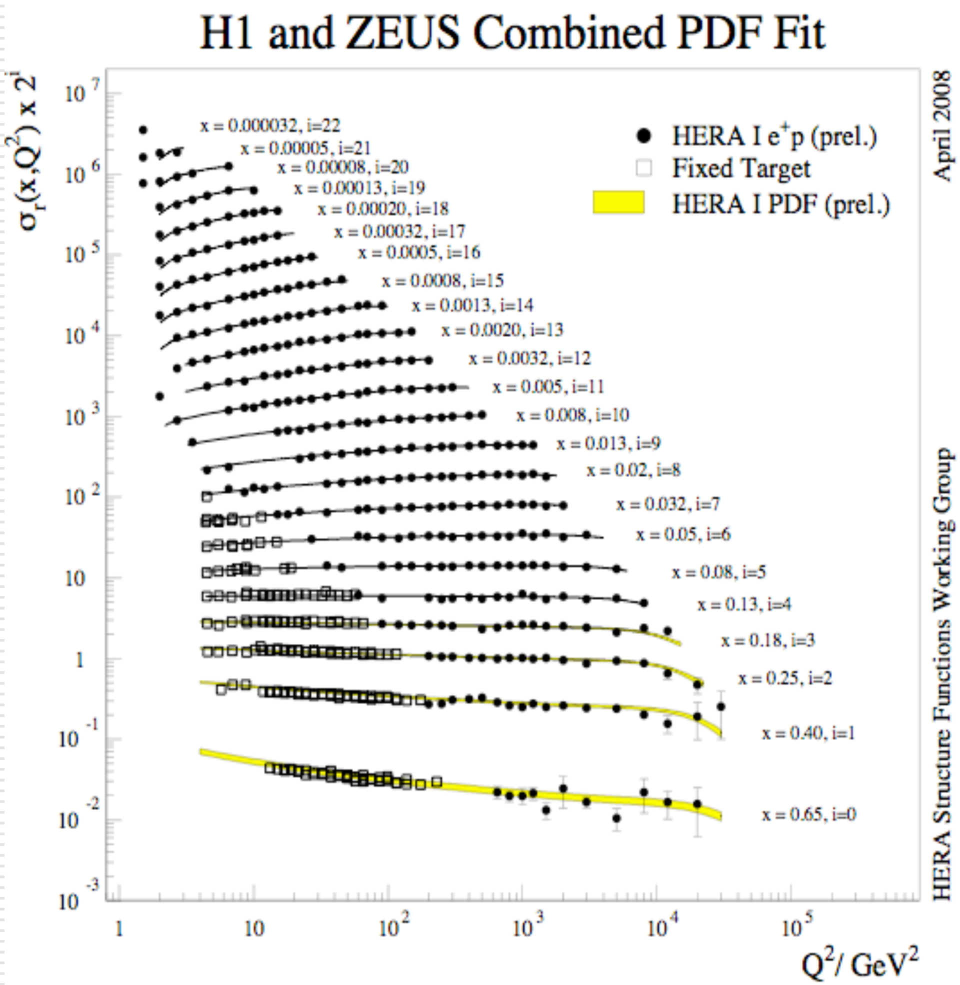
- Experimental uncertainties:
  - The combined data yields in smaller systematic than statistical uncertainties
  - The 43 systematic errors are combined in quadrature with the statistical errors and the 4 sources of errors from the combination are Offset.
    - $\chi^2$/dof = 476.7/562
- Following sources for the model uncertainty are considered:
  - Mc = 1.45 GeV ➔ 1.30 - 1.55 GeV
  - Mb = 4.75 GeV ➔ 4.30 - 5.00 GeV
  - $f_s$ = 0.33 ➔ 0.25 - 0.40
  - $f_c$ = 0.15 ➔ 0.10 - 0.20
  - $Q^2_0$= 4.GeV$^2$ ➔ 2.0 - 6.0 GeV$^2$
  - $Q^2_{min}$= 3.5 GeV$^2$ ➔ 2.5 - 5.0 GeV$^2$
- Results are compatible with
  - Other choices of parametrisations: a la H1PDF 2000 and ZEUS-Jets PDFs
  - Variation of the strong coupling $\alpha_S$(Mz)=0.1176 ➔ 0.1156 - 0.0196

# Fit Results

- The improved precision of the combined H1 and ZEUS data yields improved precision of the HERAPDF0.1 fit

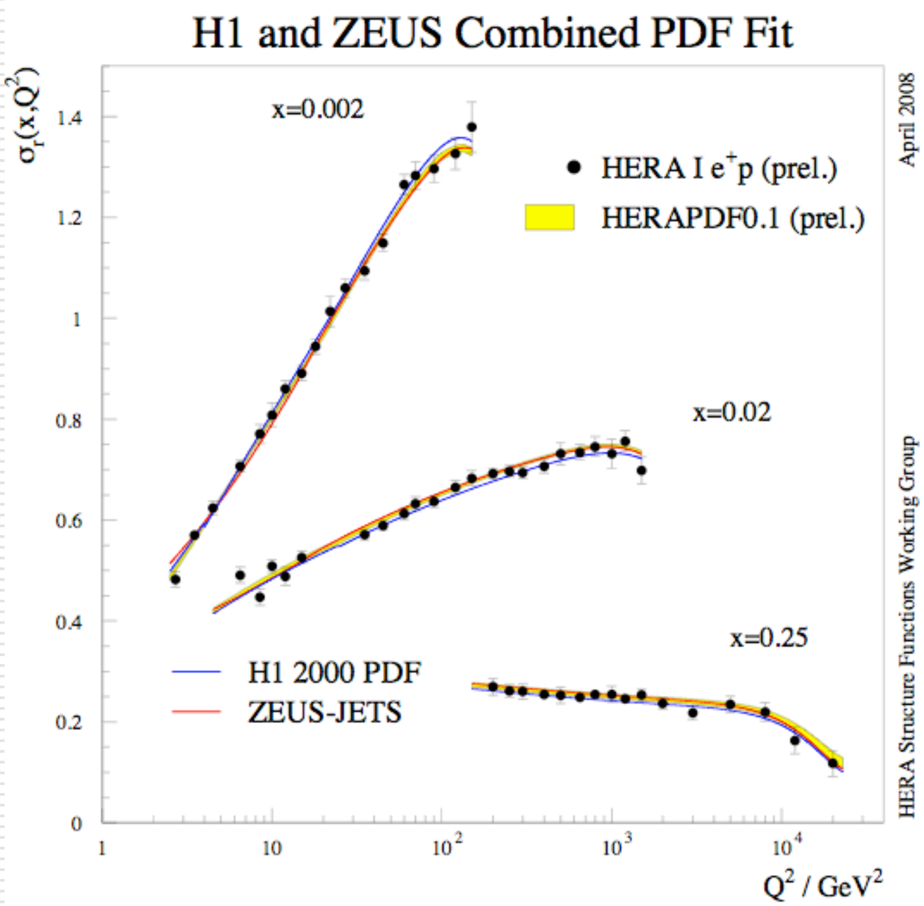
- Plots show the extended kinematic range of the HERA data as compared to the Fixed Target measurements

- Plots include uncertainties on both data and fit

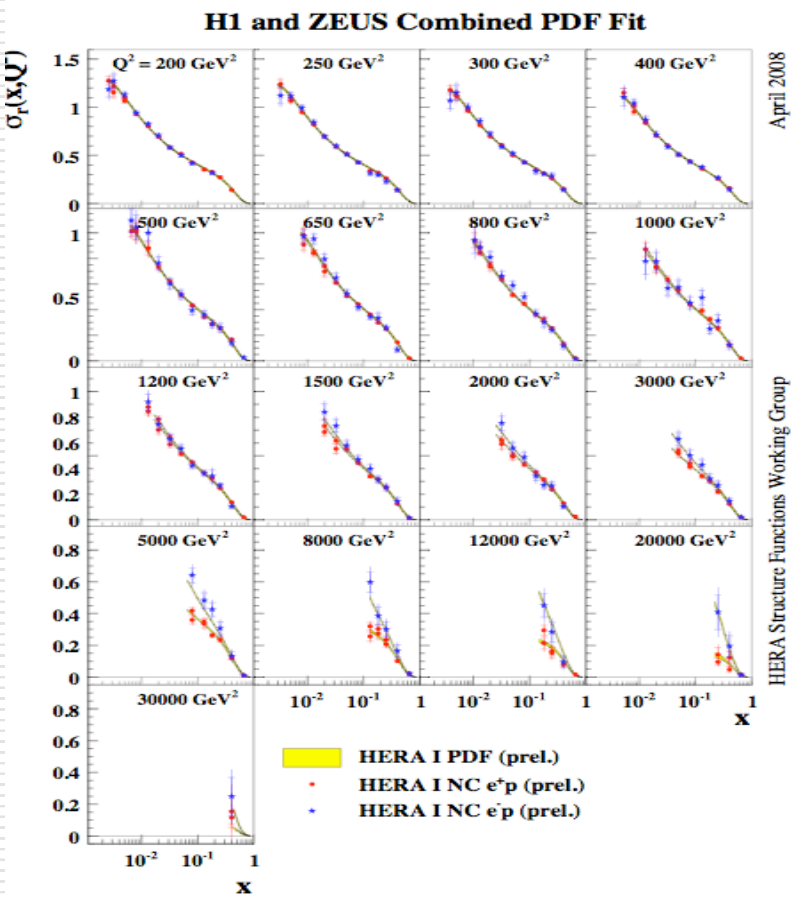


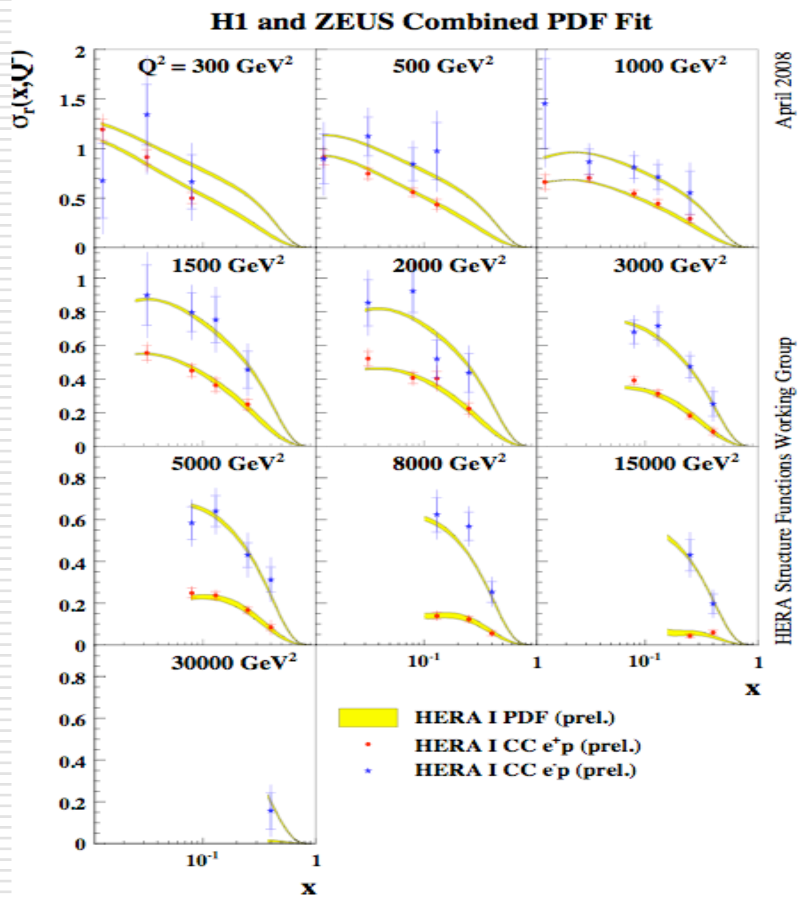
# Fit Results

- The improved precision of the combined H1 and ZEUS data yields improved precision of the HERAPDF0.1 fit
- Plots show in more detail three x bins:
  - Scaling violations
  - HERAPDF0.1 fit is compared to H1PDF 2000 and ZEUS-Jets PDFS
- Plots include uncertainties on both data and fit



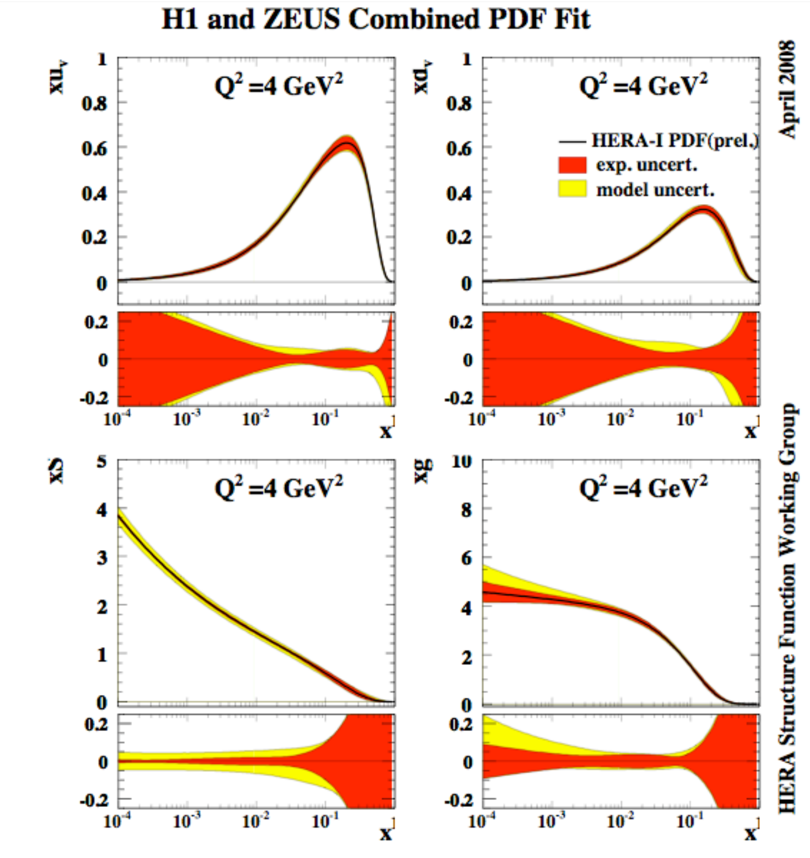
# Fit Results: NC and CC $e^{\pm}p$ data

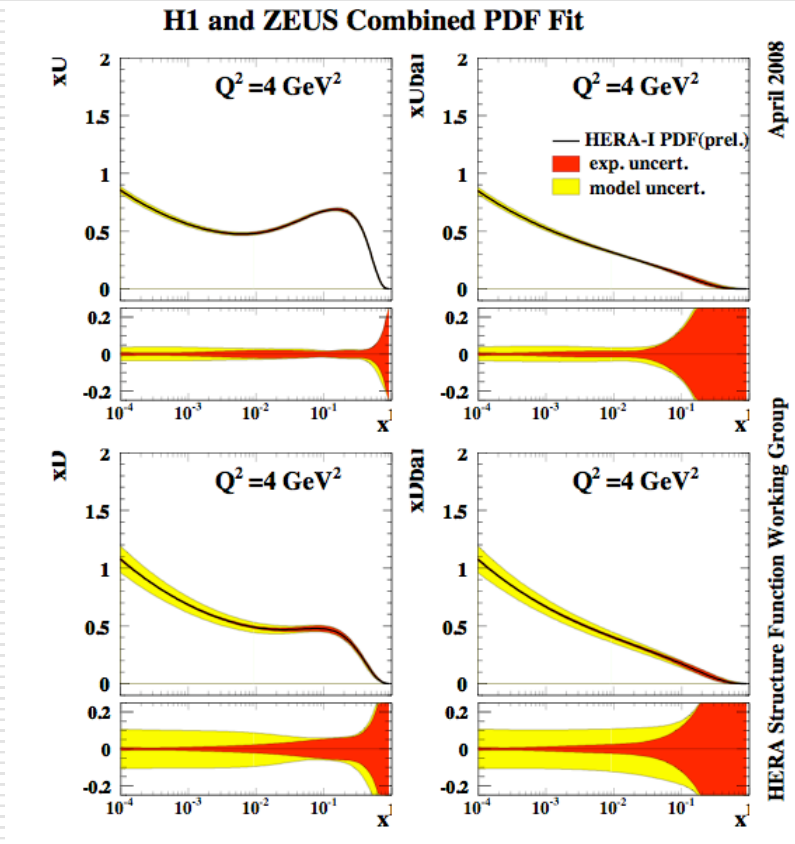



- Precision is needed to exploit the different flavour dependence of the $e^+$ and $e^-$ cross sections

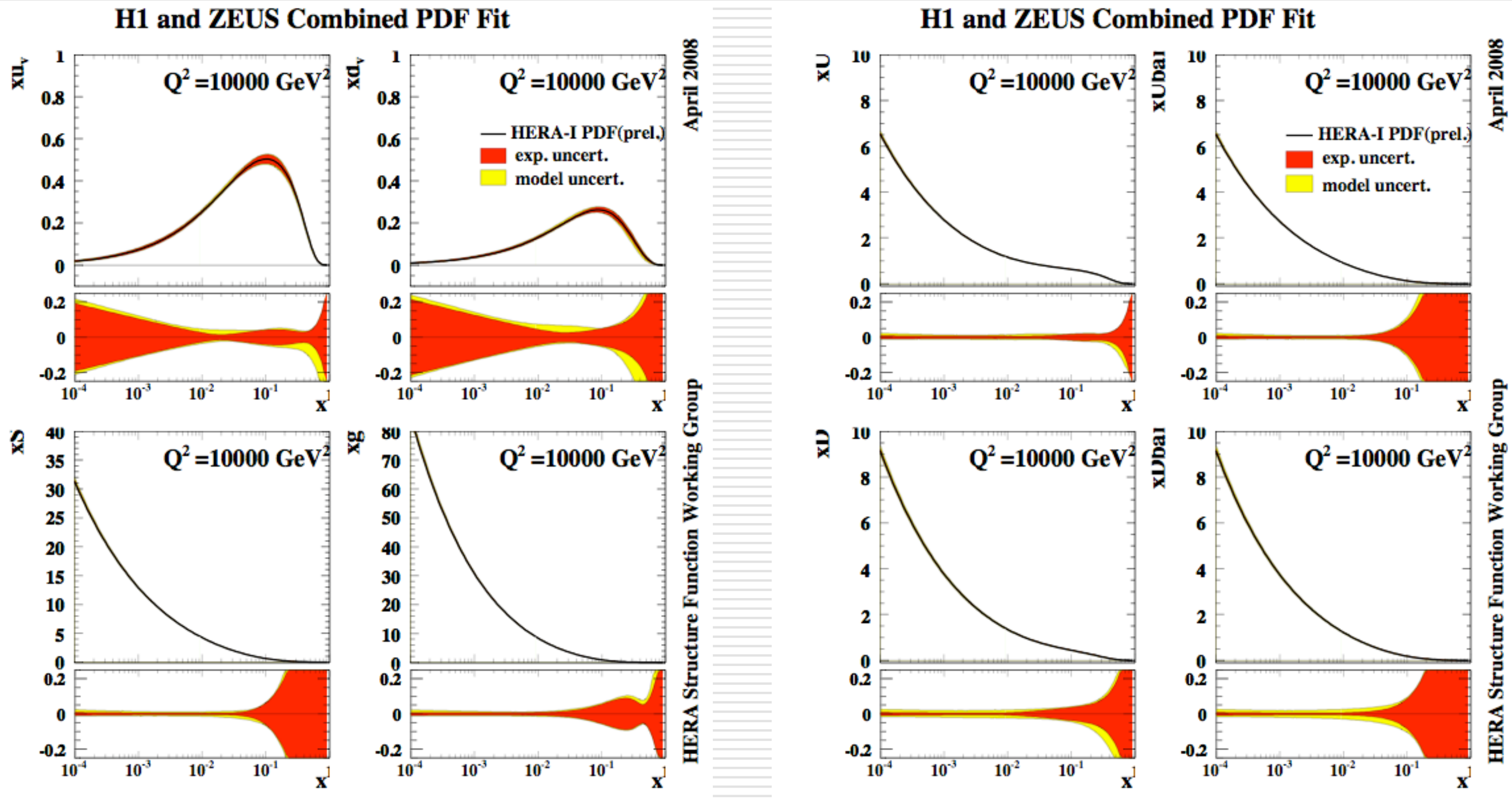
# HERAPDF0.1 at $Q^2$=4 $GeV^2$



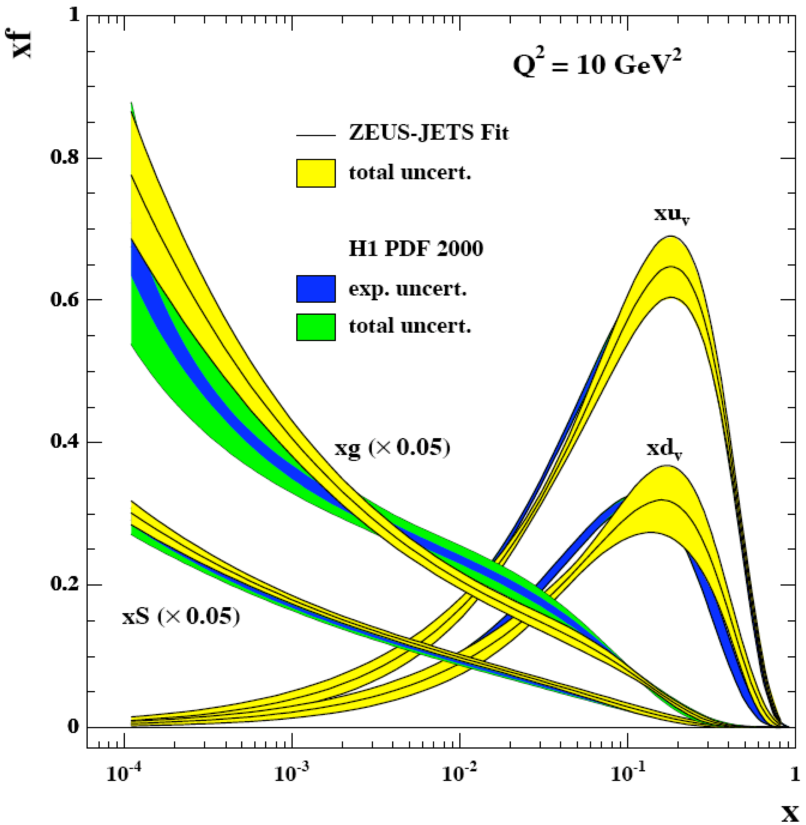

- $xu_v$, $xd_v$,xSea, xg, xU, xUbar, xD, xDbar
- Total experimental uncertainty shown in red; model uncertainty shown in yellow
  - $f_s$ dominates model uncertainty of the sea PDFs
  - $Q^2_0$, $Q^2_{min}$ dominate model uncertainty of the valence and gluon PDFs

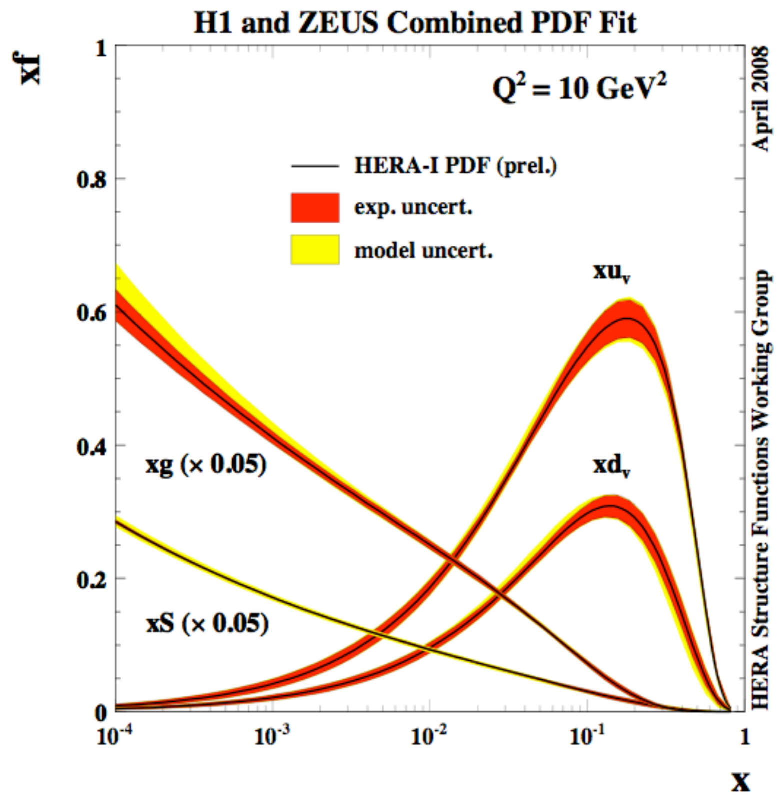
# HERAPDF0.1 at $Q^2$=10000 $GeV^2$




- Uncertainties decrease with increasing $Q^2$
- Impressive precision at the scale relevant for the LHC

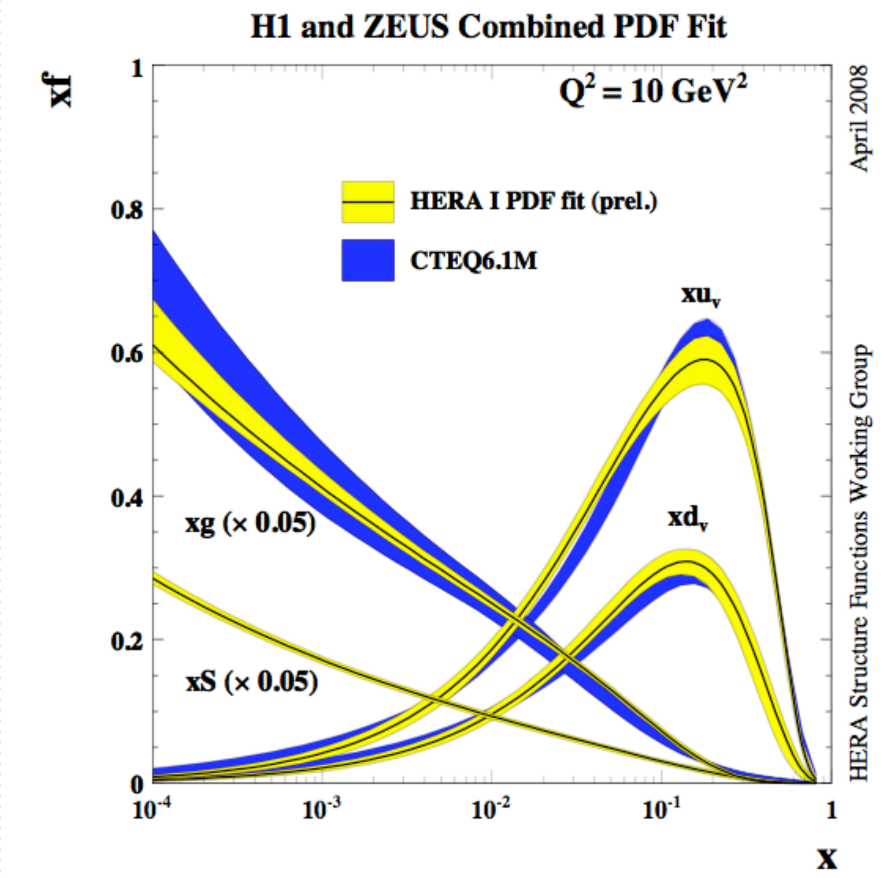
# HERAPDF0.1 vs H1PDF2000 and ZEUS-Jets

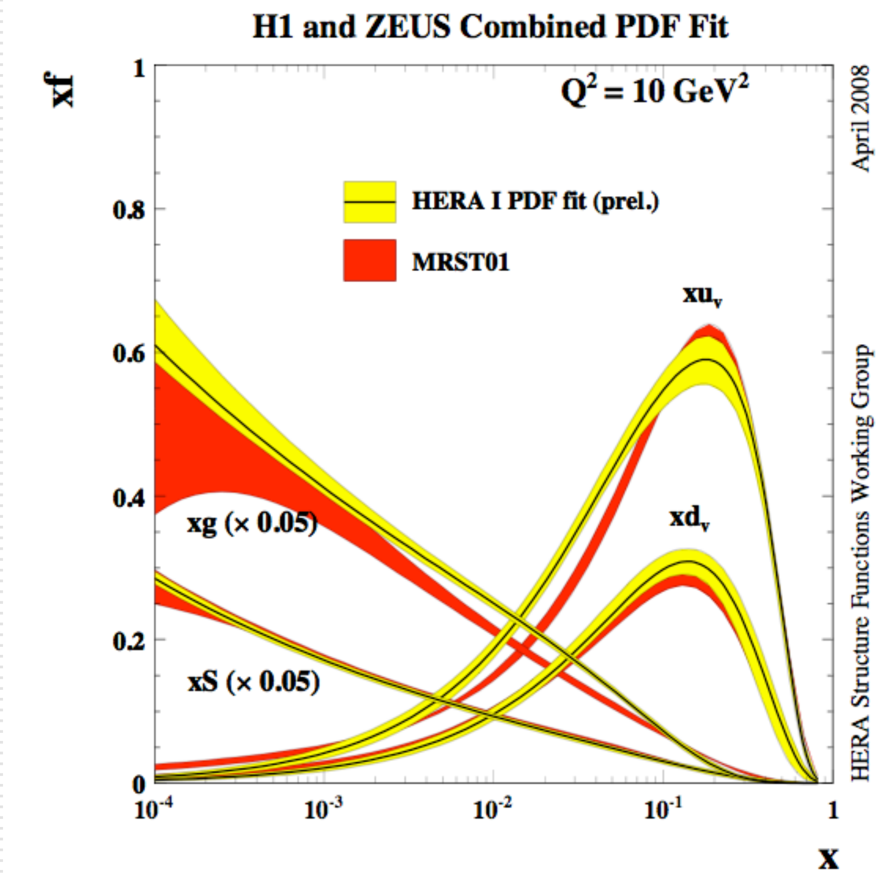



- Impressive precision for the HERAPDF0.1 as result of data combination compared to H1PDF 2000 (includes variation of the strong coupling in the model uncertainty) - in blue/green and ZEUS-Jets PDFs - in yellow

# HERAPDF0.1 vs Global Fits

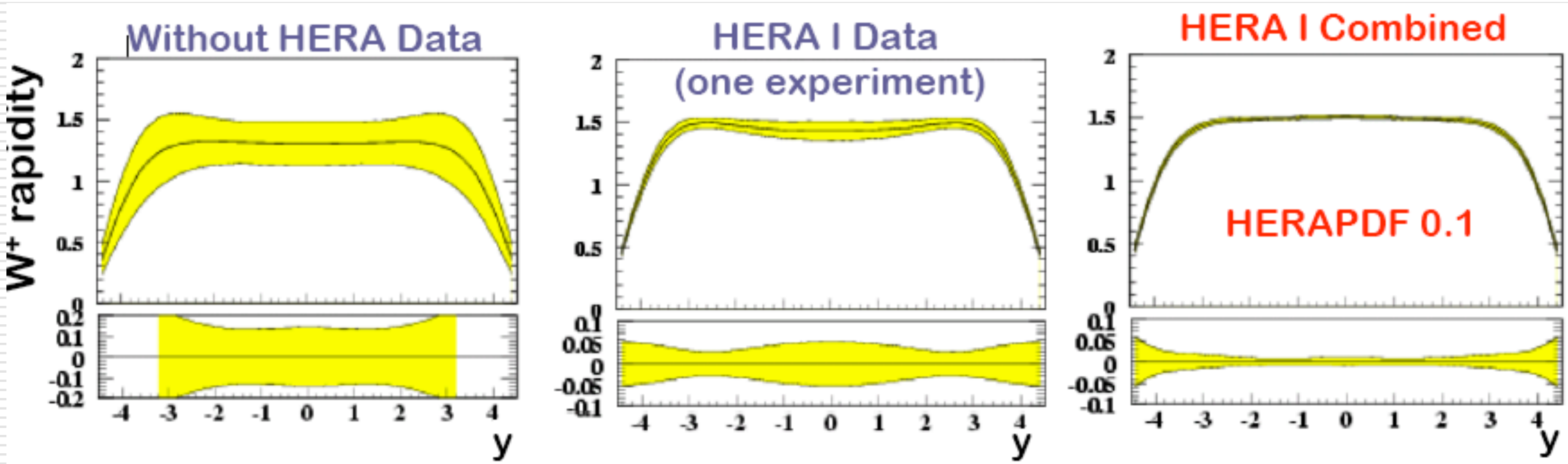



- HERAPDF0.1 is compared to CTEQ6.1M (left) and MRST01 (right)
  - The precision of HERAPDF0.1 is impressive

# Impact of HERAPDF0.1

- Discovery potential at the LHC relies on the PDF accuracy
- Simulation studies at the LHC show the impact of HERAPDF0.1 on the W production
  - The errors do not include the model uncertainty on PDFs
    [A. Cooper-Sakar & E. Perez HERA-LHC May 2008]



# Summary and outlook

- A model-independent averaging method has been developed to combine the H1 and ZEUS NC and CC cross sections (HERA-I)
  - This results in a consistent data set with significantly reduced systematic and statistical uncertainties
- The precise combined HERA-I data is further used in the NLO QCD fits to extract a more precise PDFs - HERAPDF0.1
  - The fit to HERA-I data alone has no need for target mass and heavy target corrections
  - impressive precision of the HERAPDF0.1 is observed as compared to the separate H1, ZEUS PDFs and to the global fits
- Stay tuned for even higher precision HERA cross section measurements and PDFs to come!