

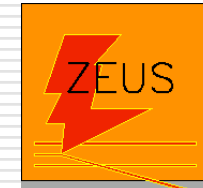


# Combined H1-ZEUS Data and the HERA PDFs



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On behalf of the H1 and ZEUS Collaborations



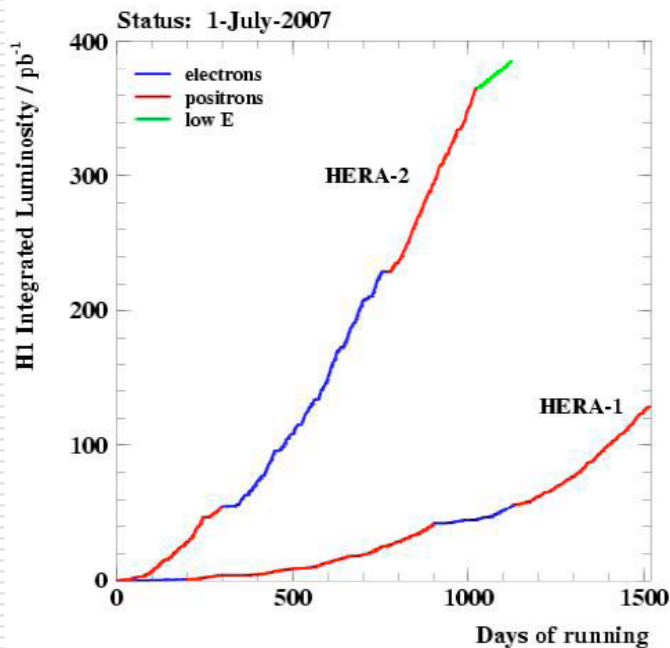
## Outline:

- 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

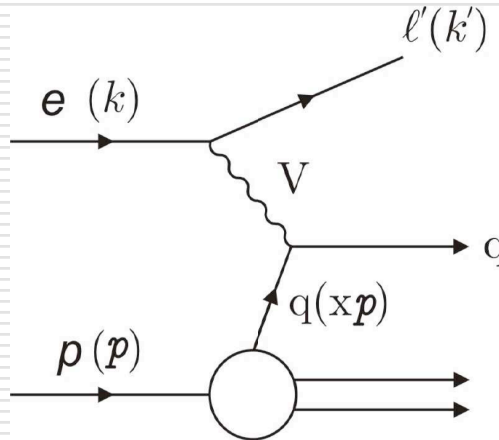


HERA-I	1992-2000	$E_p=820,920$ GeV
HERA-II	2003-2007	$E_p=920,460,575$ GeV

Only HERA-I data is used in this analysis  
( $\sim 115$  pb<sup>-1</sup> of integrated luminosity per experiment)



# 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:

$$\sigma_r(x, Q^2) = \frac{d^2\sigma(e^\pm p)}{dx dQ^2} \frac{Q^4 x}{2\pi\alpha^2 Y_\pm} = F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2) \mp \frac{Y_-}{Y_+} x F_3(x, Q^2)$$

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

- $F_2$  - dominates: sensitive to sea and valence
- $F_L$  - contributes at high y: sensitive to gluon
- $x F_3$  - contributes at high  $Q^2$ : sensitive to valence



# Combination of H1 & ZEUS data - Motivation

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- 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)
  - $E_p = 820$  ( $\sqrt{s}=301$ ) and  $920$  ( $\sqrt{s}=319$ ) GeV,  $L = 240 \text{ pb}^{-1}$
- Kinematic coverage:  $1.5 < Q^2 < 30000 \text{ GeV}^2$  and  $0.00006 < x < 0.65$

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



# Cross sections prior combination

□ H1 and ZEUS published precise measurements of the NC and CC DIS cross sections

■ For  $Q^2 < 100 \text{ GeV}^2$ :

□ Stat error  $< 1\%$

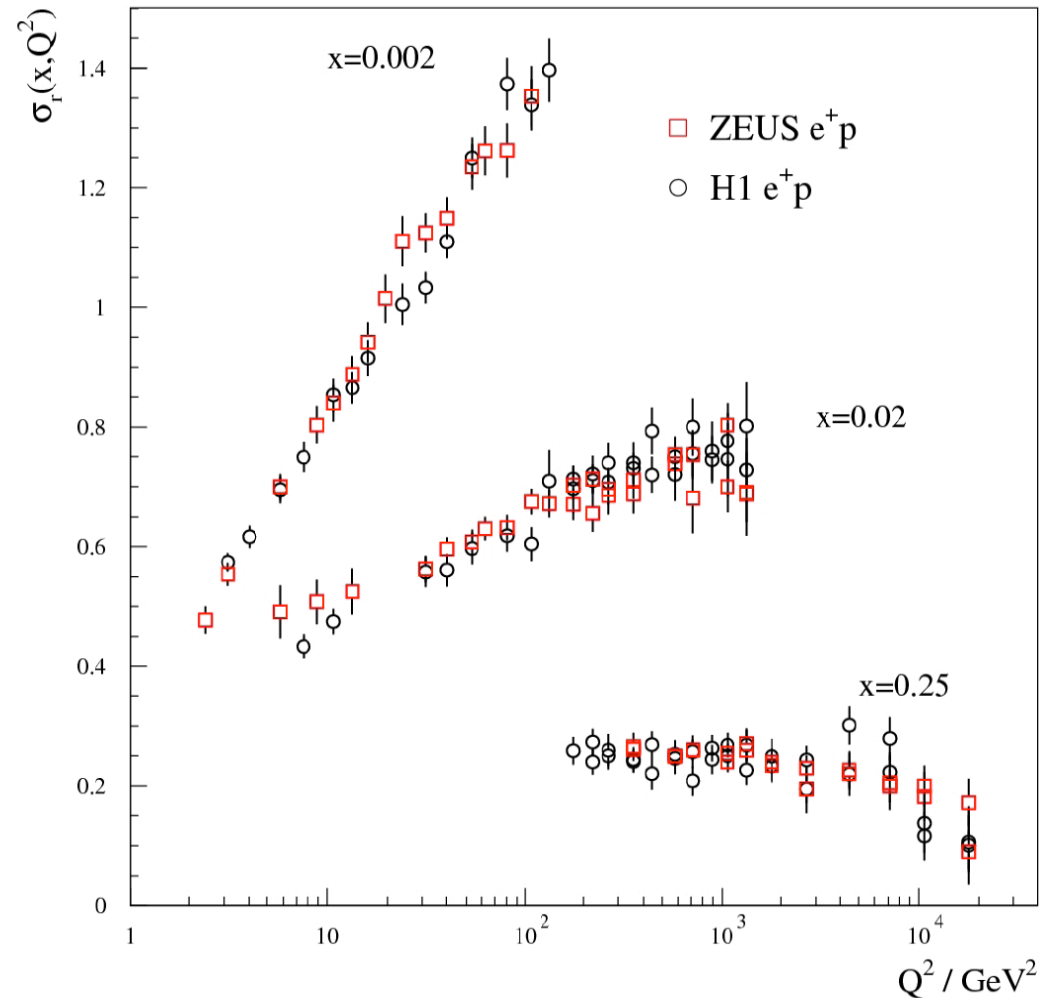
□ Sys error  $< 3\%$

■ For  $Q^2 > 1000 \text{ GeV}^2$ :

□ Stat error  $>$  Sys error

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

HERA I  $e^+p$  Neutral Current Scattering – H1 and ZEUS





# Averaging Method (I)

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- 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:

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

- $M^i$  - 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  $j$
- $M^{i,\text{true}}$  - true value we determine
  
- By construction:  $\chi^2 = 0$  for  $M^{i,\text{true}} = M^i$  &  $\alpha_j = 0$
- 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  $\delta_i \longrightarrow \frac{M^{i,\text{true}}}{M^i} \delta_i$





# Uncertainties

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- Uncorrelated uncertainties:
  - Statistical errors
  - Point-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

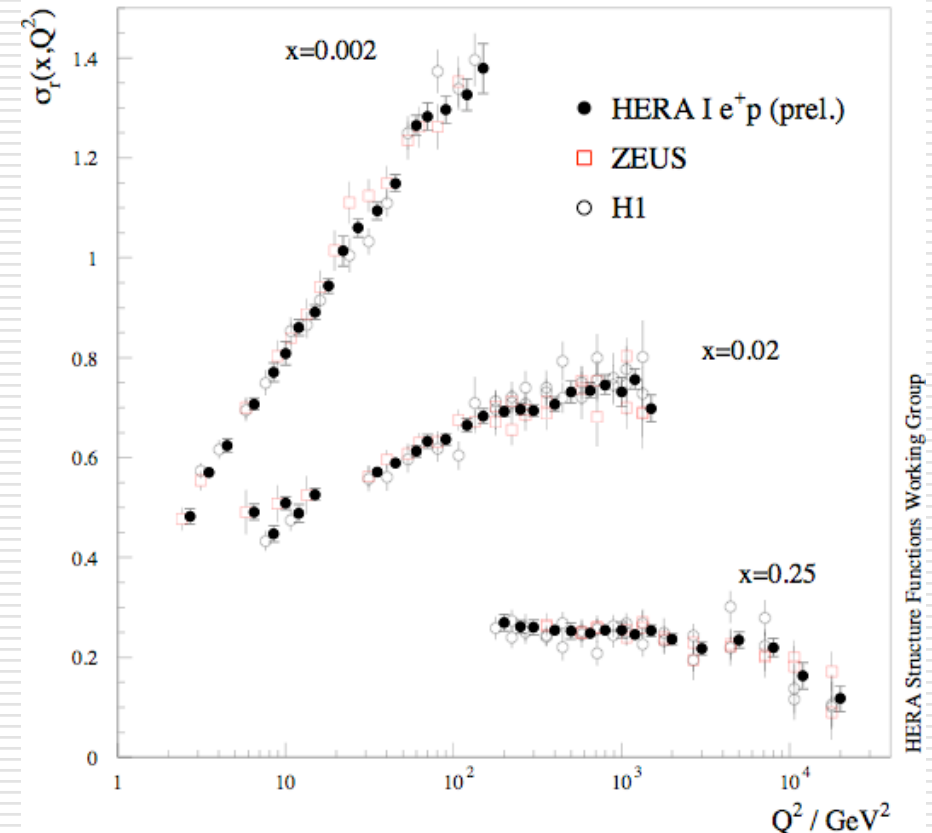


# Results

- 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  $Q^2$  96-97- shifted up by  $1.6\sigma$
- Overall precision improved:
  - $Q^2 < 12 \text{ GeV}^2$ :  $< 2\%$  precision
  - $Q^2 \sim 100 \text{ GeV}^2$ :  $1.5\%$  precision
  - For highest  $Q^2$ :  $10\%$  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 $x$

HERA I  $e^+p$  Neutral Current Scattering - H1 and ZEUS



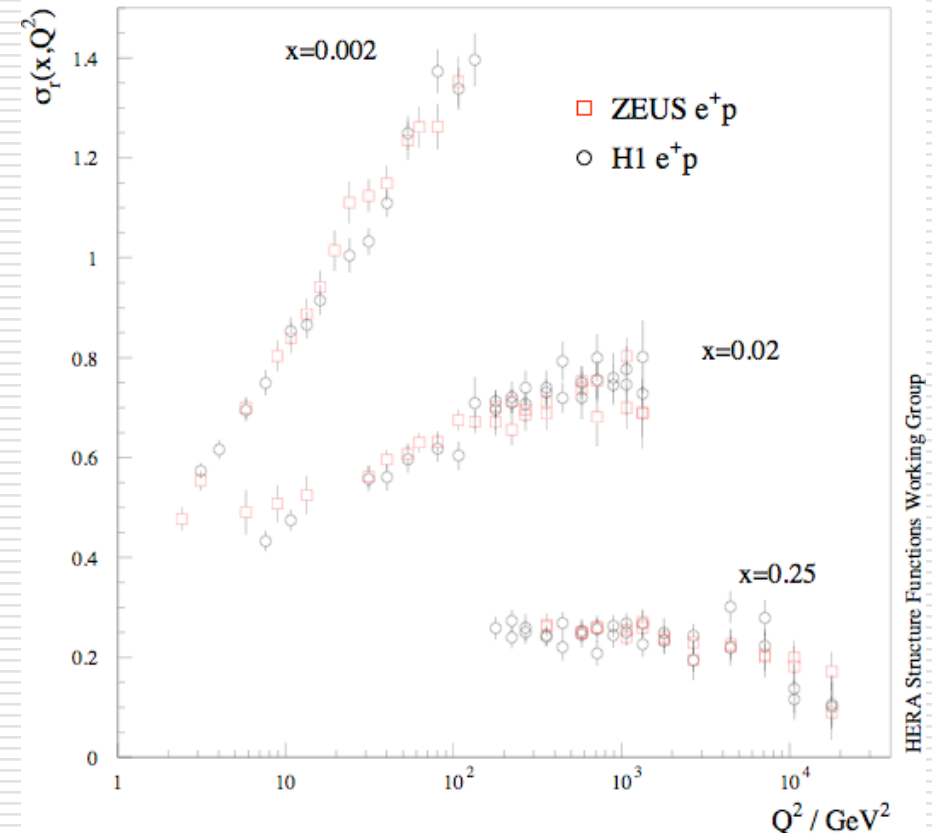


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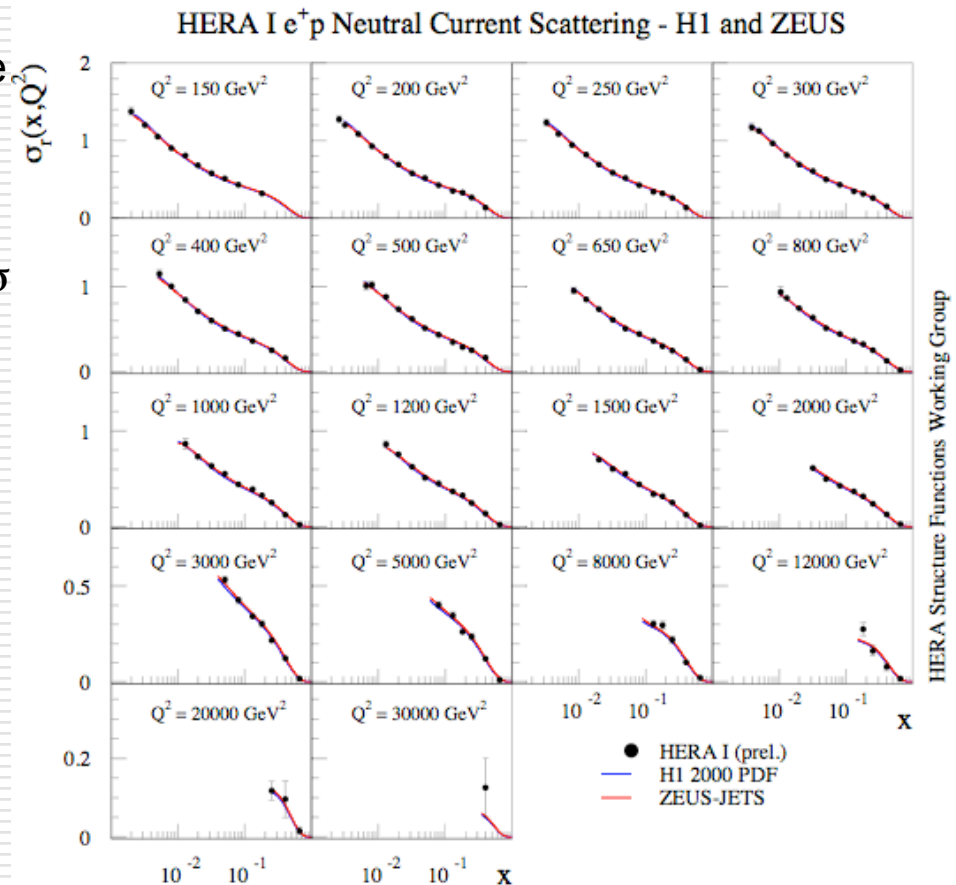




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- Most significant improvements
  - H1 backward calo energy scale (x3)
  - ZEUS forward energy flow modeling (x4)
- H1PDF 2000 and ZEUS-Jets PDFs describe well the combined data

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





# QCD Analysis

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## □ 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  $Q_0^2$  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 <sub>v</sub>	Sum rule	FIT	FIT	FIT	FIT
xd <sub>v</sub>	Sum rule	=B(xu <sub>v</sub> )	FIT		
x $\bar{U}$	$\lim_{x \rightarrow 0} \bar{U}/\bar{D} \rightarrow 1$	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

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- NLO predictions using DGLAP evolution equations
- The input scale  $Q_0^2 = 4 \text{ GeV}^2$
- Calculations in Zero-mass variable-number flavour scheme
- Renormalisation and Factorisation scales set to the  $Q^2$
- The choices for heavy quark masses:  $M_c = 1.4 \text{ GeV}$ ,  $M_b = 4.75 \text{ GeV}$
- The strong coupling  $\alpha_s = 0.1176$  [PDG 2006]
- Minimum  $Q^2 = 3.5 \text{ GeV}^2$



# Uncertainties

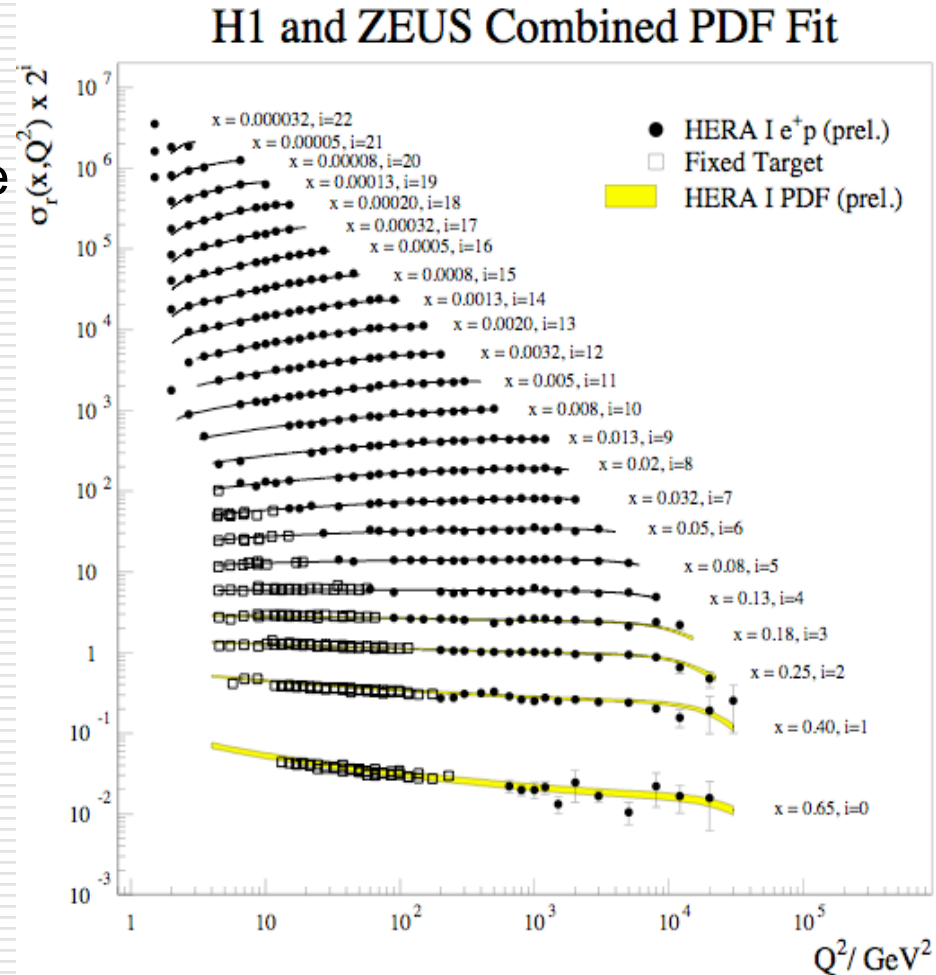
- Experimental uncertainties:
  - The combined data yields in smaller systematic than statistical uncertainties
  - The 43 systematic errors are combined in quadrature with the statistical errors and the 4 sources of errors from the combination are Offset.
    - $\chi^2/\text{dof} = 476.7/562$
- Following sources for the model uncertainty are considered:
  - $M_c = 1.45 \text{ GeV} \rightarrow 1.30 - 1.55 \text{ GeV}$
  - $M_b = 4.75 \text{ GeV} \rightarrow 4.30 - 5.00 \text{ GeV}$
  - $f_s = 0.33 \rightarrow 0.25 - 0.40$
  - $f_c = 0.15 \rightarrow 0.10 - 0.20$
  - $Q_0^2 = 4. \text{GeV}^2 \rightarrow 2.0 - 6.0 \text{ GeV}^2$
  - $Q_{\text{min}}^2 = 3.5 \text{ GeV}^2 \rightarrow 2.5 - 5.0 \text{ GeV}^2$
- Results are compatible with
  - Other choices of parametrisations: a la H1PDF 2000 and ZEUS-Jets PDFs
  - Variation of the strong coupling  $\alpha_s(M_z) = 0.1176 \rightarrow 0.1156 - 0.0196$





# 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



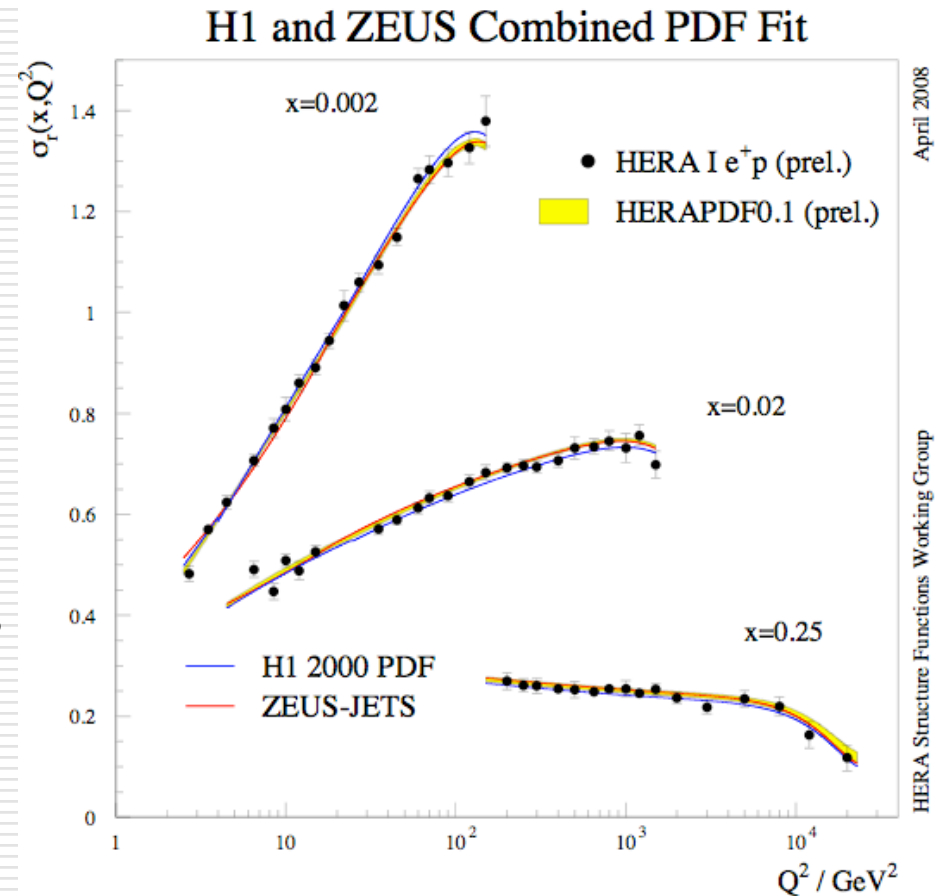
April 2008

HERA Structure Functions Working Group



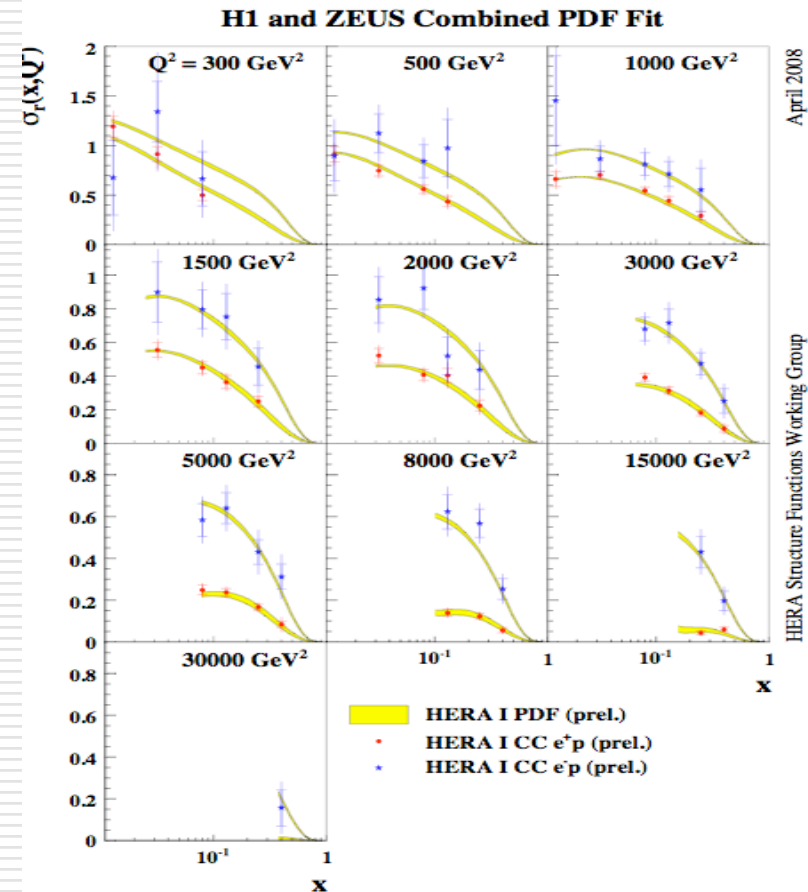
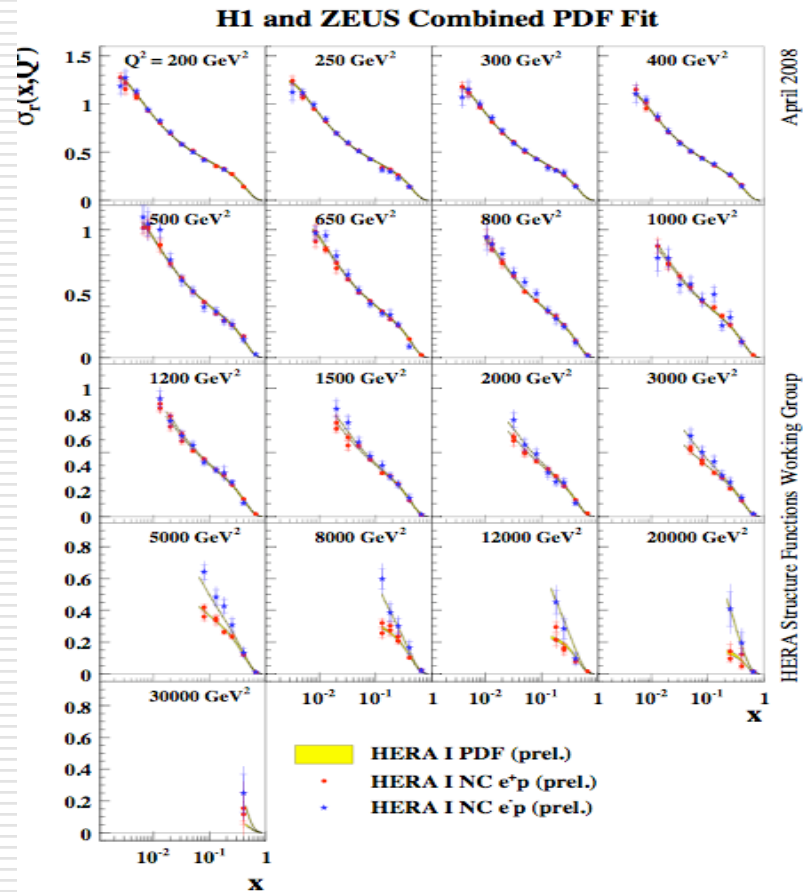
# Fit Results

- 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





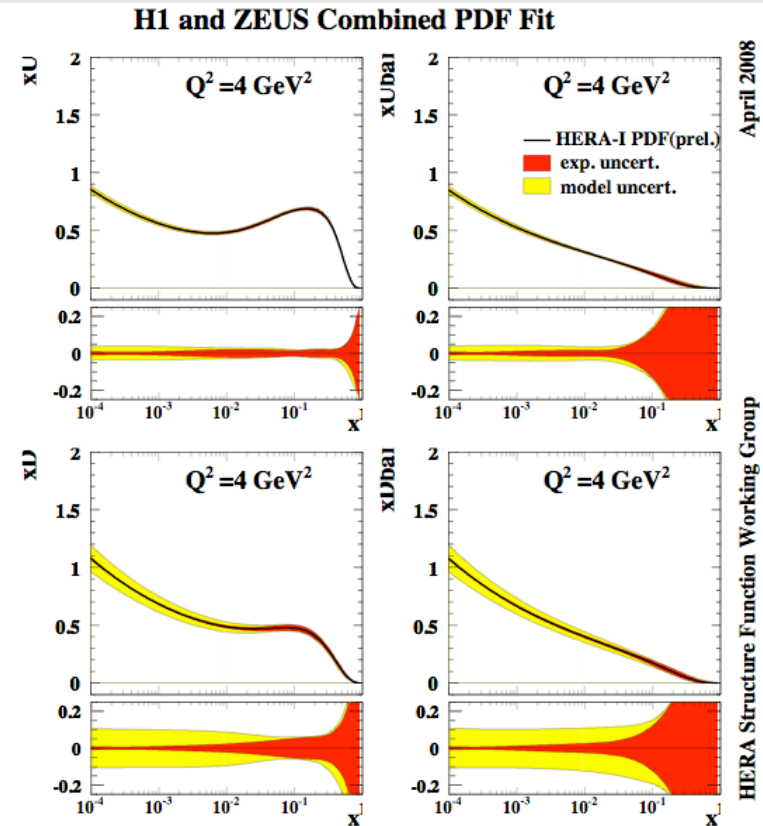
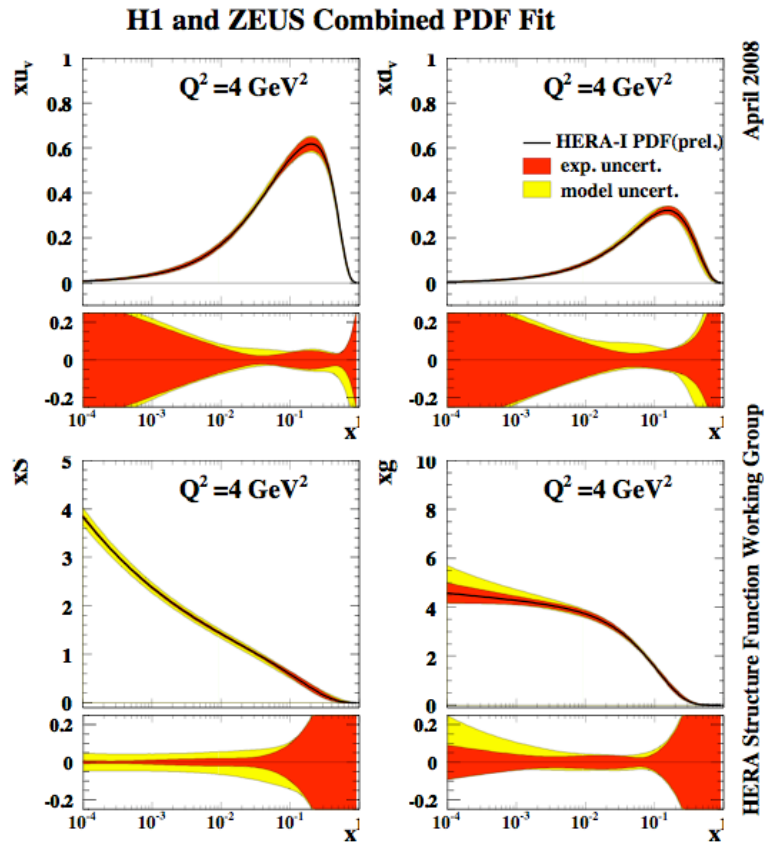
# Fit Results: NC and CC $e^\pm p$ data



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



# HERAPDF0.1 at $Q^2=4 \text{ GeV}^2$

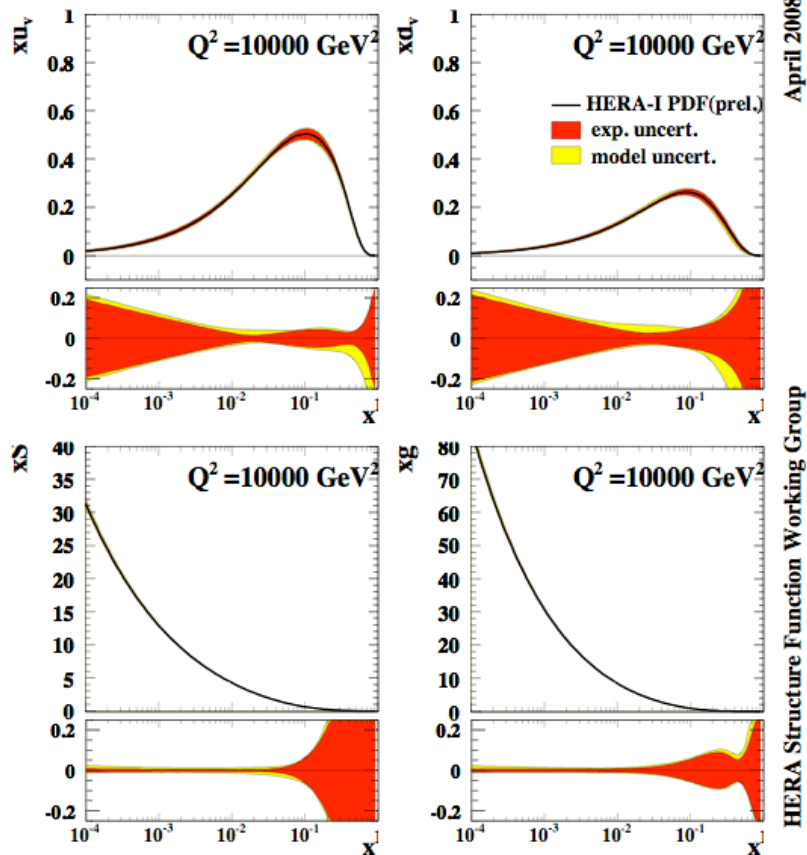


- $xu_v, xd_v, x\text{Sea}, xg, xU, xUbar, xD, xDbar$
- Total experimental uncertainty shown in red; model uncertainty shown in yellow
  - $f_s$  dominates model uncertainty of the sea PDFs
  - $Q^2_0, Q^2_{\min}$  dominate model uncertainty of the valence and gluon PDFs

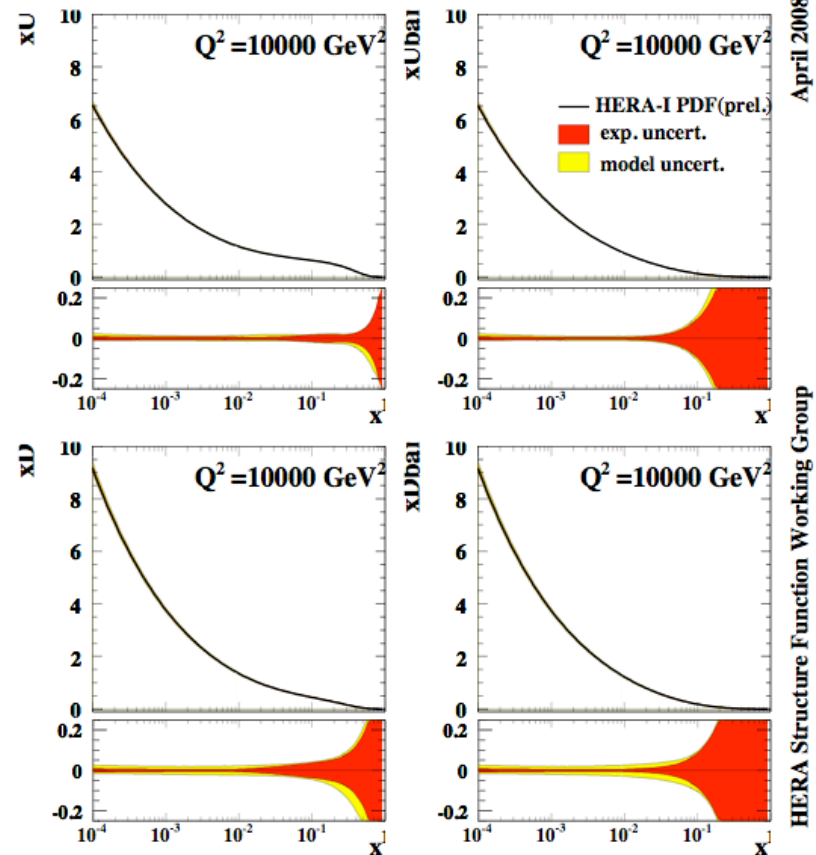


# HERAPDF0.1 at $Q^2=10000 \text{ GeV}^2$

H1 and ZEUS Combined PDF Fit



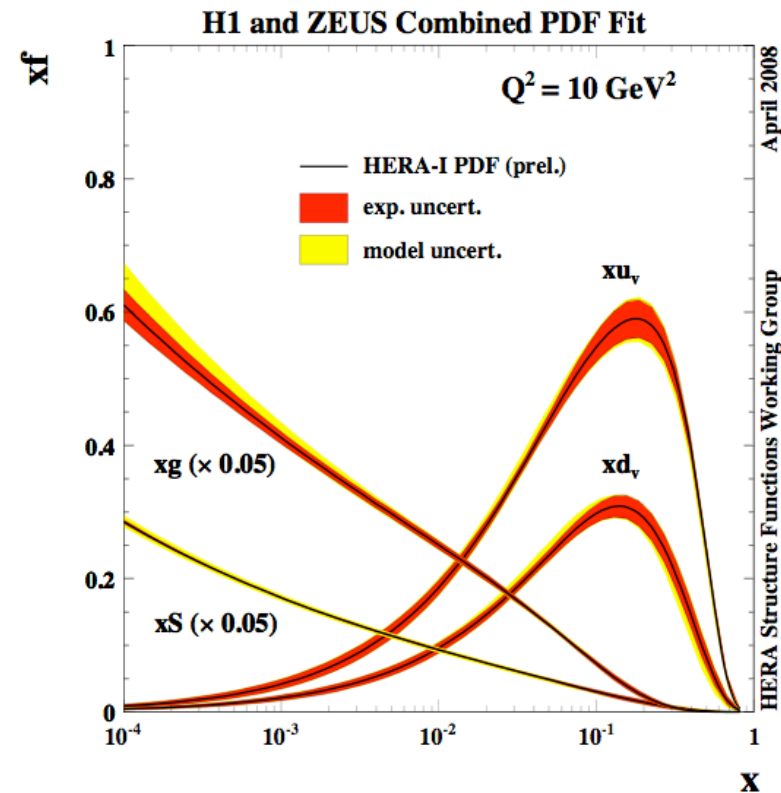
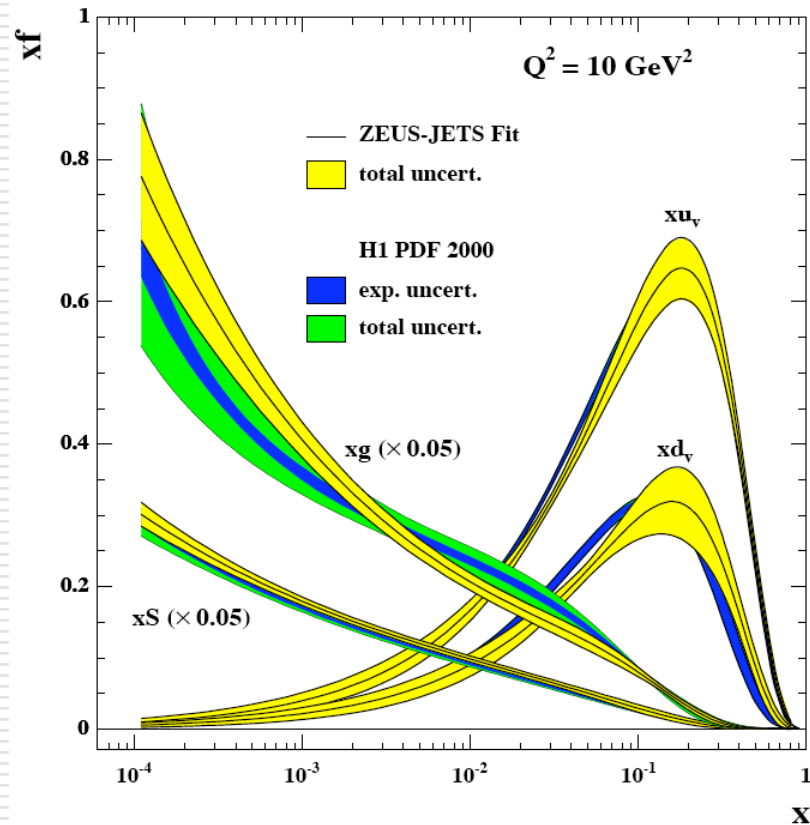
H1 and ZEUS Combined PDF Fit



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



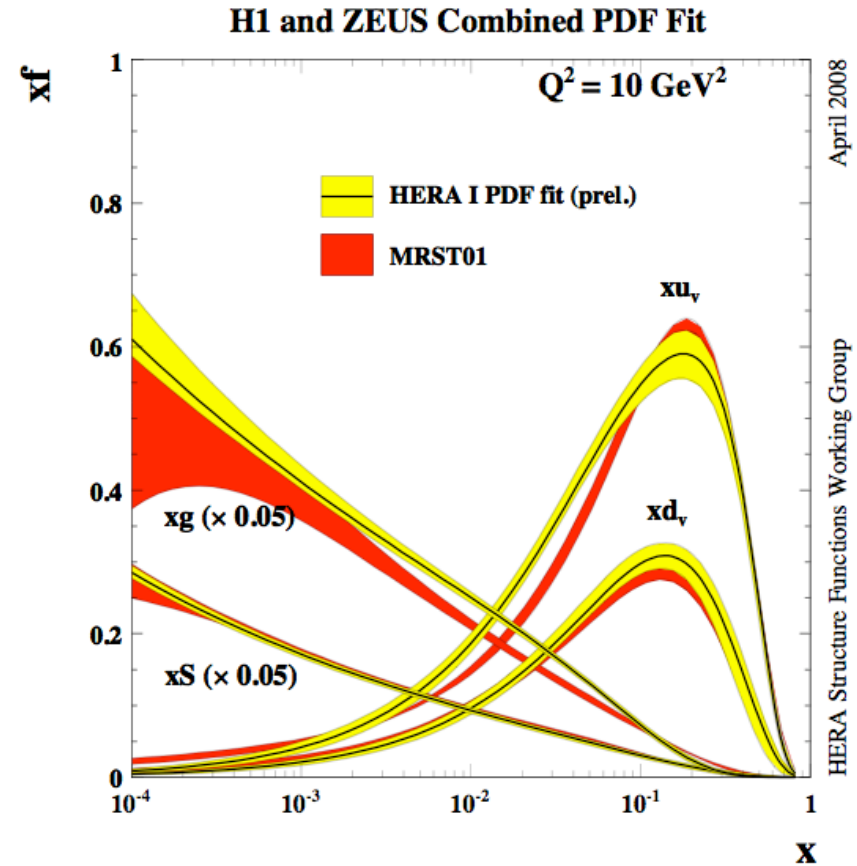
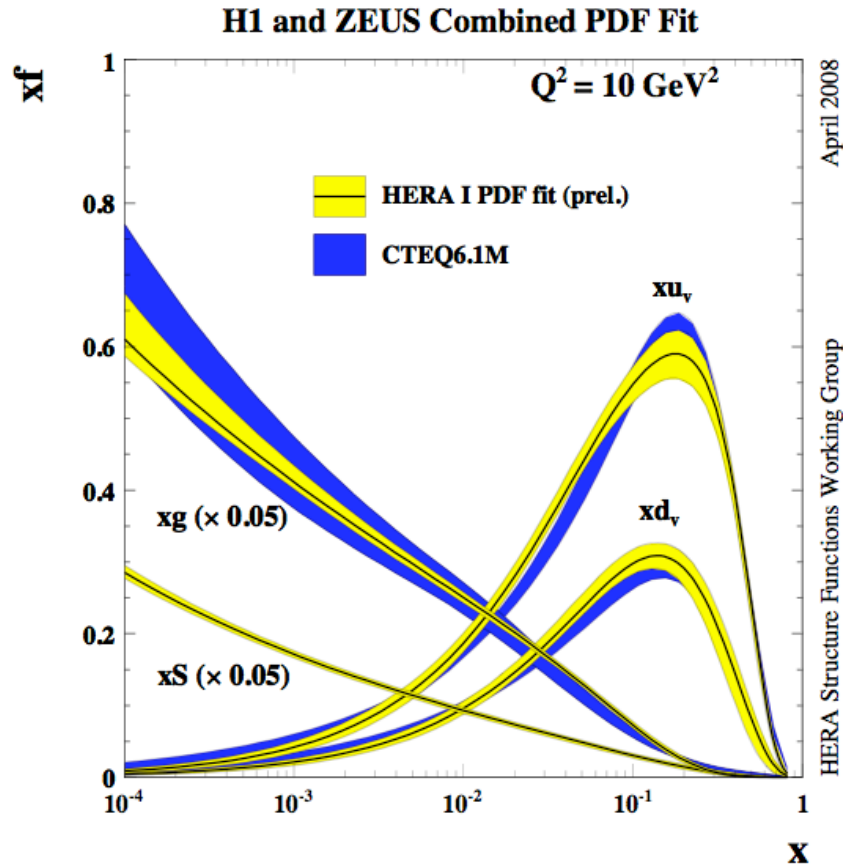
# HERAPDF0.1 vs H1PDF2000 and ZEUS-Jets



- 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

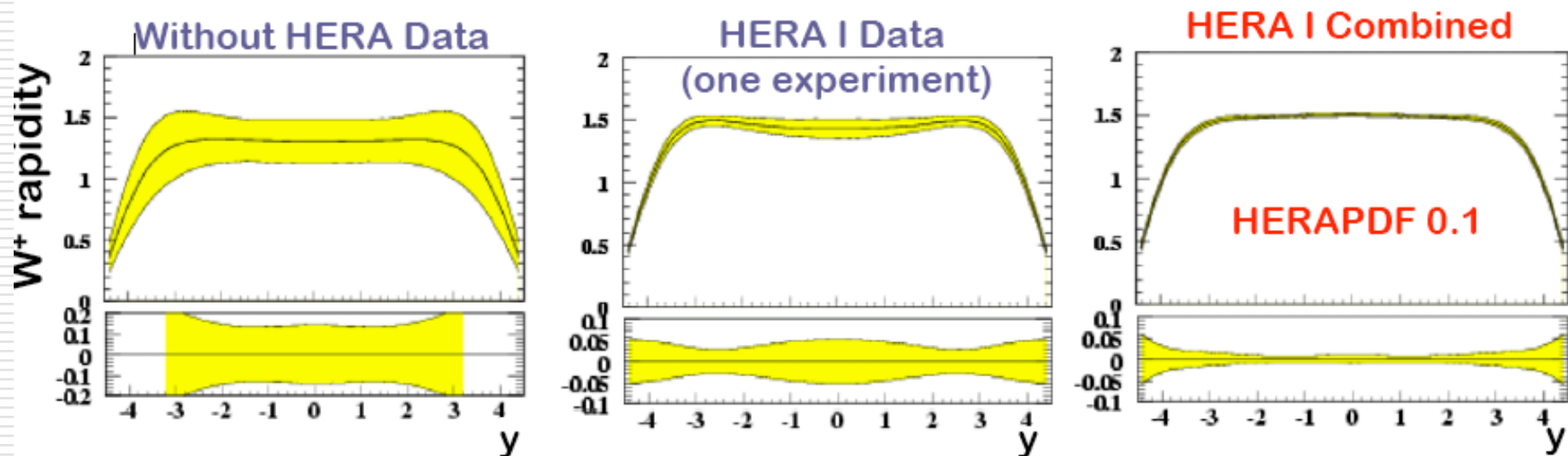


- HERAPDF0.1 is compared to CTEQ6.1M (left) and MRST01 (right)
- The precision of HERAPDF0.1 is impressive



# 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

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- 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!