Combination of H1 and ZEUS Deep Inelastic $e^{\pm}p$ Scattering Cross Section Measurements and NLO-QCD Fit Analysis

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On behalf of the H1 and ZEUS Collaborations

HERA Structure Function Working Group

Outline:

- Introduction
- Data Sets and Combination
- NLO QCD Fit Analysis
- Results and Comparisons
- Summary

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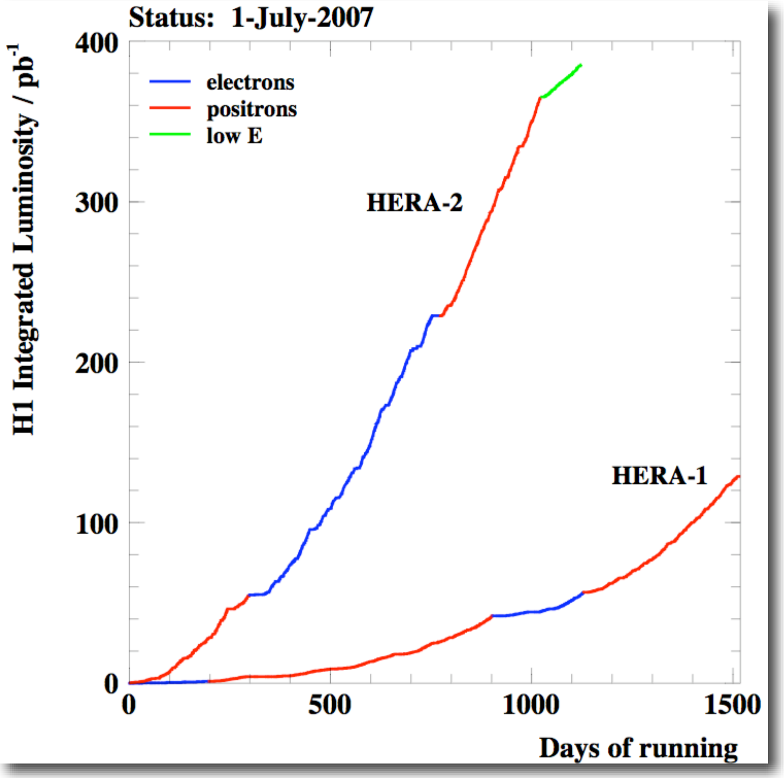
HERA at DESY

- HERA is an *ep* collider at DESY
  - o In operation for 15 years until June 2007
- 4 experiments:
  - o Fixed Target: HERMES and HERA-B
  - o Collider: 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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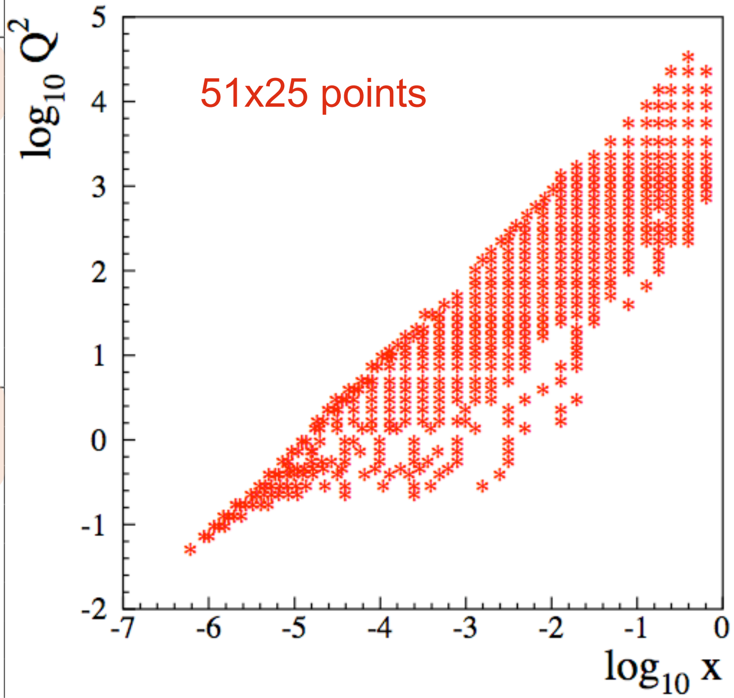
Introduction

- MOTIVATION
  - produce a more consistent and precise cross section measurement to be used in QCD analysis to extract precise HERA PDF sets
    - New HERA PDF to complete the HERA I inclusive data!
- DATA SETS:
  - Published HERA-I inclusive NC and CC DIS data (1994-2000)
    - 1% precision for the combined data in the 10-100 GeV^2 region

Data Set		x range		Q^2 range GeV^2		$\mathcal{L}$ pb^{-1}	$\sqrt{s}$ GeV
H1 svx-mb	95-00	5×10^{-6}	0.02	0.2	12	2.1	301-319
H1 low Q^2	96-00	2×10^{-4}	0.1	12	150	22	301-319
H1 NC	94-97	0.0032	0.65	150	30000	35.6	301
H1 CC	94-97	0.013	0.40	300	15000	35.6	301
H1 NC	98-99	0.0032	0.65	150	30000	16.4	319
H1 CC	98-99	0.013	0.40	300	15000	16.4	319
H1 NC HY	98-99	0.0013	0.01	100	800	16.4	319
H1 NC	99-00	0.00131	0.65	100	30000	65.2	319
H1 CC	99-00	0.013	0.40	300	15000	65.2	319
ZEUS BPT	97	6×10^{-7}	0.001	0.045	0.65	3.9	301
ZEUS BPC	95	2×10^{-6}	6×10^{-5}	0.11	0.65	1.65	301
ZEUS SVX	95	1.2×10^{-5}	0.0019	0.6	17	0.2	301
ZEUS CC	94-97	0.015	0.42	280	17000	47.7	301
ZEUS NC	96-97	6×10^{-5}	0.65	2.7	30000	30.0	301
ZEUS NC	98-99	0.005	0.65	200	30000	15.9	319
ZEUS CC	98-99	0.015	0.42	280	30000	16.4	319
ZEUS NC	99-00	0.005	0.65	200	30000	63.2	319
ZEUS CC	99-00	0.008	0.42	280	17000	60.9	319



Data Combination Strategy

- Swim all points to a common x-Q^2 grid
- Move 820 GeV data to 920 GeV p-beam energy
- Calculate average values and uncertainties [arXiv:0904.0929]
- Evaluate “procedural uncertainties”

The combination of data uses the χ^2 minimisation method

- Additive error sources:

$$\chi^2_{\rm exp}(\boldsymbol{m},\boldsymbol{b}) = \sum_i \frac{\left[m^i - \sum_j \Gamma^i_j b_j - \mu^i\right]^2}{\Delta_i^2} + \sum_j b_j^2.$$

- Multiplicative error sources:
  - small biases to lower cross sections values avoided by a modified χ^2 definotion

$$\chi^2_{\rm exp}(\boldsymbol{m},\boldsymbol{b}) = \sum_i \frac{\left[m^i - \sum_j \gamma^i_j m^i b_j - \mu^i\right]^2}{\delta^2_{i,\rm stat}\left(m^i - \sum_j \gamma^i_j m^i b_j\right) + \left(\delta_{i,\rm uncor}\, m^i\right)^2} + \sum_j b_j^2.$$

- Measured central values μ_i
- Relative correlated systematic uncertainties $\gamma^i_j = \Gamma^i_j/\mu^i$
- Relative statistical uncertainties $\delta_{i,\rm stat} = \Delta_{i,\rm stat}/\mu^i$
- Relative uncorrelated systematic uncertainties $\delta_{i,\rm uncor} = \Delta_{i,\rm uncor}/\mu^i$

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1. Additive vs Multiplicative nature of the error sources
    - typically below 0.5%

A general study of the possible correlated systematic uncertainties between H1 and ZEUS has been performed:

- Identified 12 possible uncertainties of common origin
- Compare 2^{12} averages taking all pairs as corr./uncorr. in turn.

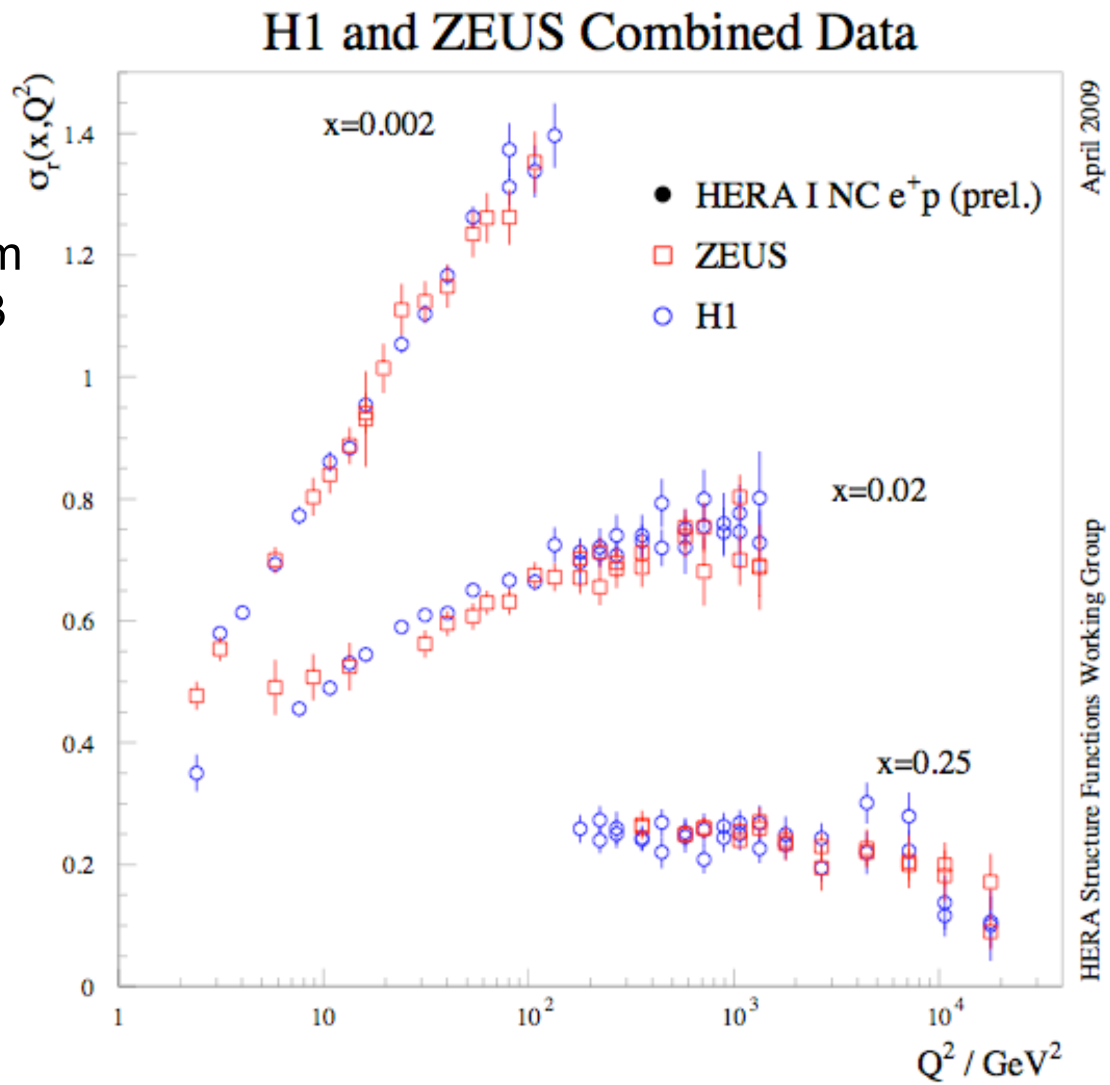
Mostly negligible except for:

2. Correlated systematic unc. for the photoproduction background
    - few % only at high-y
3. Correlated systematic unc. for the hadronic energy scale
    - at the ‰ level

Resulting Averaged HERA I Data

- 1402 points are combined to 741 unique cross section measurements
  - χ^2/ndf = 637/656
  - 110 systematic sources from separate experiments and 3 from the combining procedure

- Overall precision improved:
  - For $3<Q^2<500$ GeV^2
    - 2% precision
  - For $20<Q^2<100$ GeV^2
    - 1% precision



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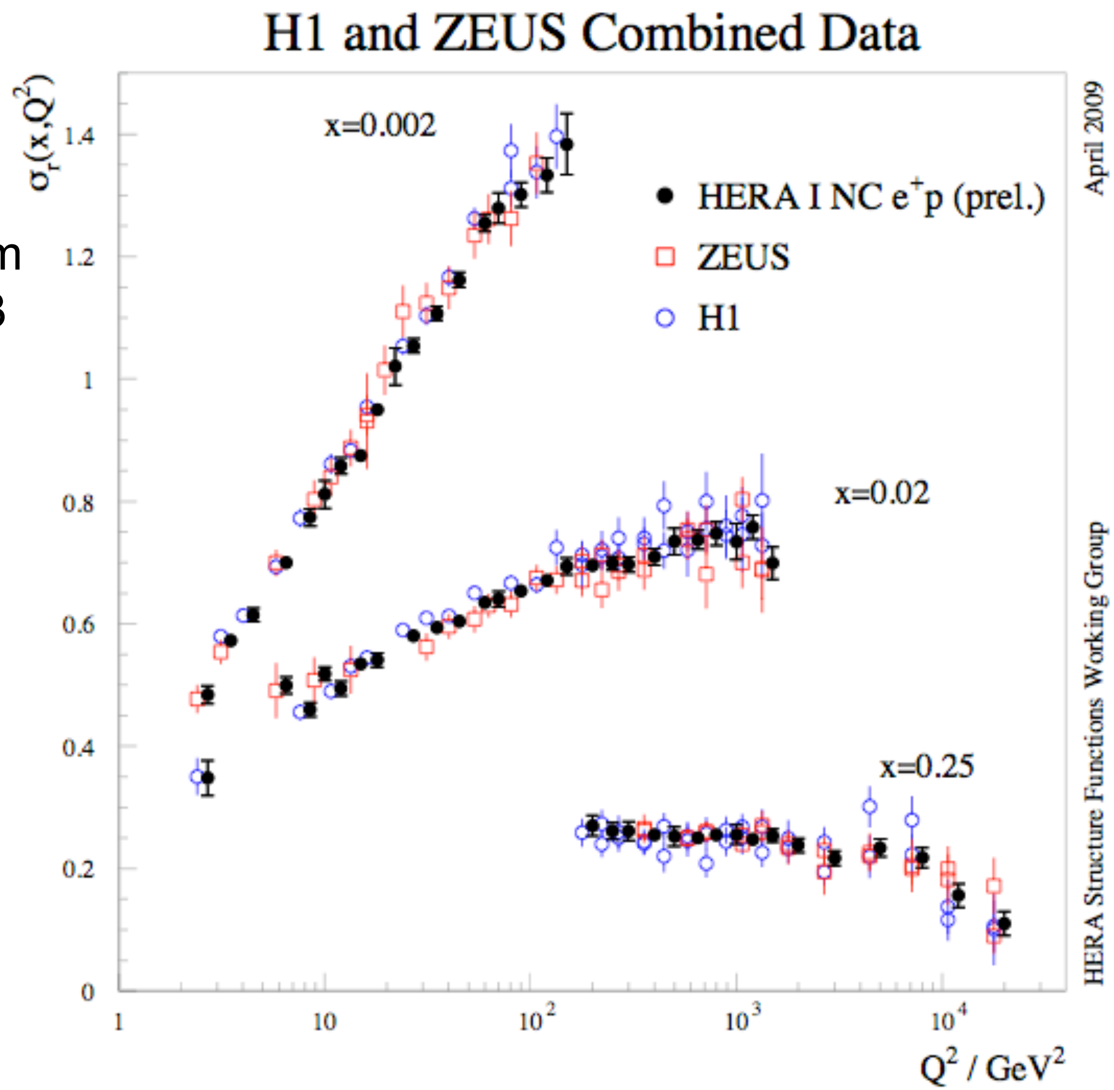


QCD Analysis Framework

- Combined HERA I Data is a sole input in the fit!

- NLO predictions using DGLAP equations in MS
  - QCDNUM17.02 (M. Botje): can do NNLO fits
  - Starting scale $Q_0 < M_c$

- Structure Function calculations in General-Mass Variable Flavour Number Scheme (GMVFNS)
  - ➢ Thorne-Roberts VFNS 2008
  - An improved theoretical treatment of heavy quarks which takes the quark masses into account

Scheme	TRVFNS
Evolution	QCDNUM17.02
Order	NLO
Q_0^2	1.9 GeV^2
$f_s = s/D$	0.31
Renorm. scale	Q^2
Factor. scale	Q^2
Q^2_{min}	3.5 GeV^2
$\alpha_S(M_Z)$	0.1176
M_c	1.4 GeV
M_b	4.75 GeV

- Parametrisation form of the PDFs: $\mathrm{gluon}, \mathrm{u_{val}}, \mathrm{d_{val}}, \overline{\mathrm{U}} = \bar{\mathrm{u}} + \bar{\mathrm{c}}, \overline{\mathrm{D}} = \bar{\mathrm{d}} + \bar{\mathrm{s}} + \bar{\mathrm{b}}$

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

The optimum number of parameters chosen by saturation of the χ^2 (i.e. only parameters that significantly contribute to χ^2 are let to vary)

- ➢ 10 free parameters for central fit!
- ➢ χ^2/dof=576/592

PDF	A	B	C	D	E
xg	sum rule	FIT	FIT	-	-
xu_{val}	sum rule	FIT	FIT	-	FIT
xd_{val}	sum rule	$=B_{u_{val}}$	FIT	-	-
$x\bar{U}$	$\lim_{x\to 0}\bar{u}/\bar{d} \to 1$	FIT	FIT	-	-
$x\bar{D}$	FIT	$=B_{\bar{U}}$	FIT	-	-

PDF Uncertainties

- Experimental uncertainties
  - consistent data, therefore use tolerance $\Delta\chi^2=1$
  - 110 systematic errors are combined in quadrature with the statistical errors and 3 sources of errors from the averaging procedure are offset.
    - Small effects observed when errors are treated as correlated

- Model uncertainties
  - Obtained by varying the input assumptions

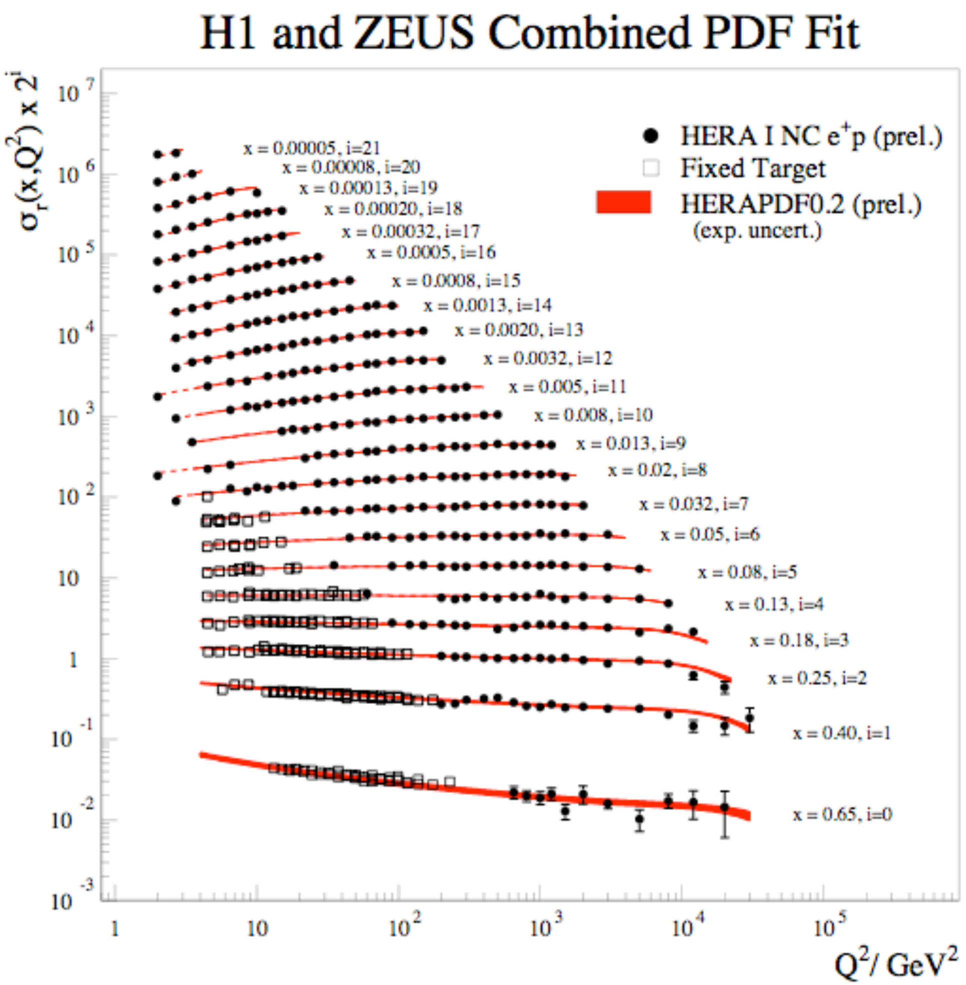
Variation	Central	Lower	Upper
m_b	4.75	4.3	5.0
Q^2_{min}	3.5	2.5	5.0
f_s	0.31	0.23	0.38
m_c	1.4	1.35	1.5
Q^2_0	1.9	1.5	2.5

- PDF parametrisation uncertainty [→J.Terron's talk]
  - alternative parametrisations with similar or better χ^2 which have been discarded due to additional optimisation requirements:
    - Reasonable shape for valence and sea distributions at high-x
    - All PDFs >0
  - Envelope of all these fits is formed and used as PDF parametrisation error
    - 7 fits out of all possible 11 parameter fits obtained by adding one additional parameter to the central fit parametrisation choice were used for the envelope

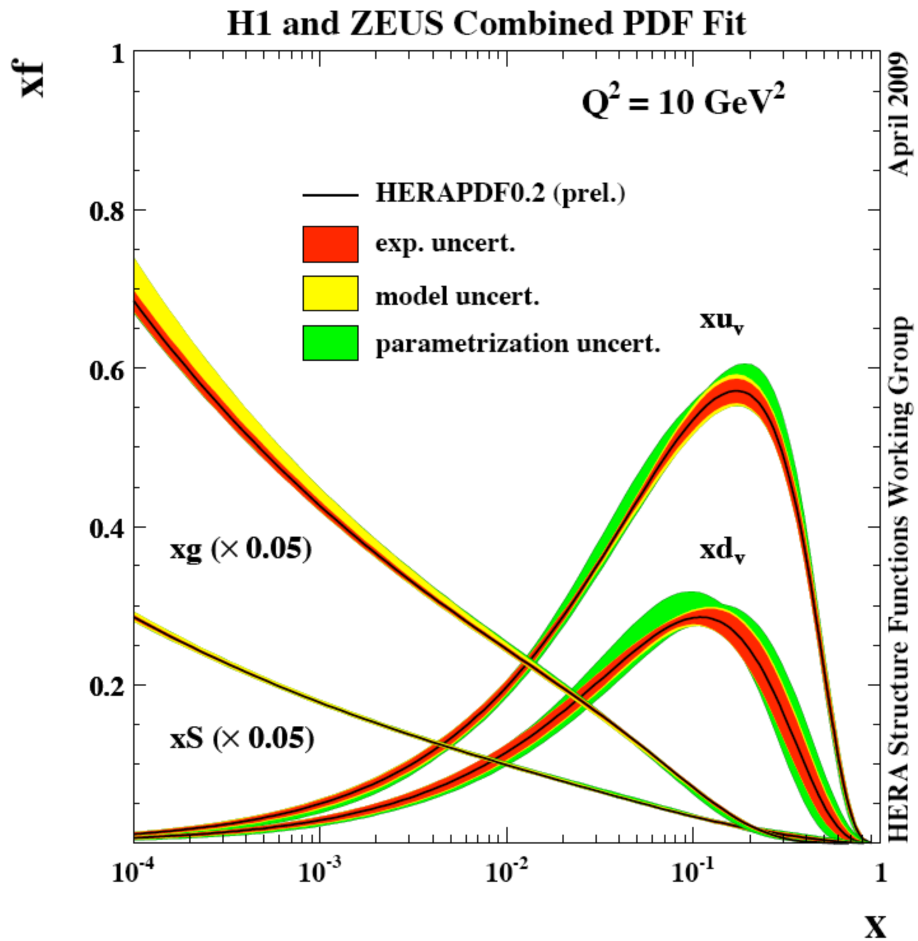
- Study variation of the strong coupling
    - $\alpha S(Mz)=0.1176 \pm 0.0020$ [PDG]

Fit Results: HERAPDF0.2

- χ^2 /dof = 576/592
- Plot show the extended kinematic range of HERA data as compared to fixed target measurements



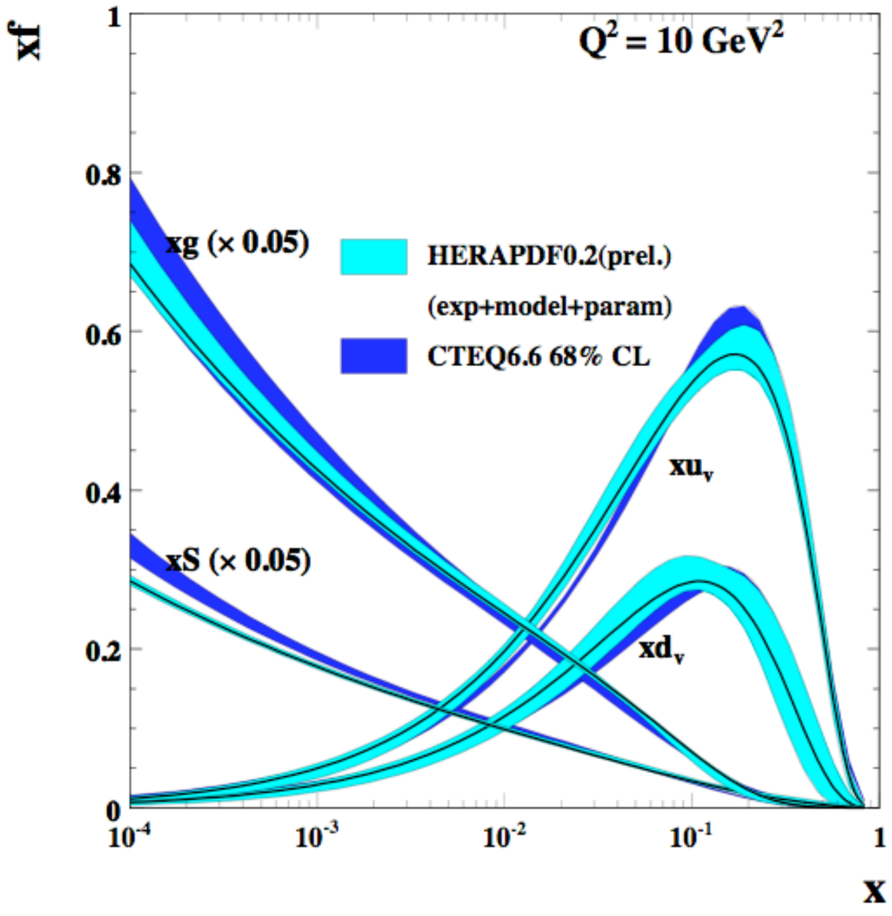
- PDF uncertainties:
  - High-x and valence are mostly affected by the PDF parametrisation uncertainty
    - Procedure addresses only high-x region!
    - Low x region is being investigated



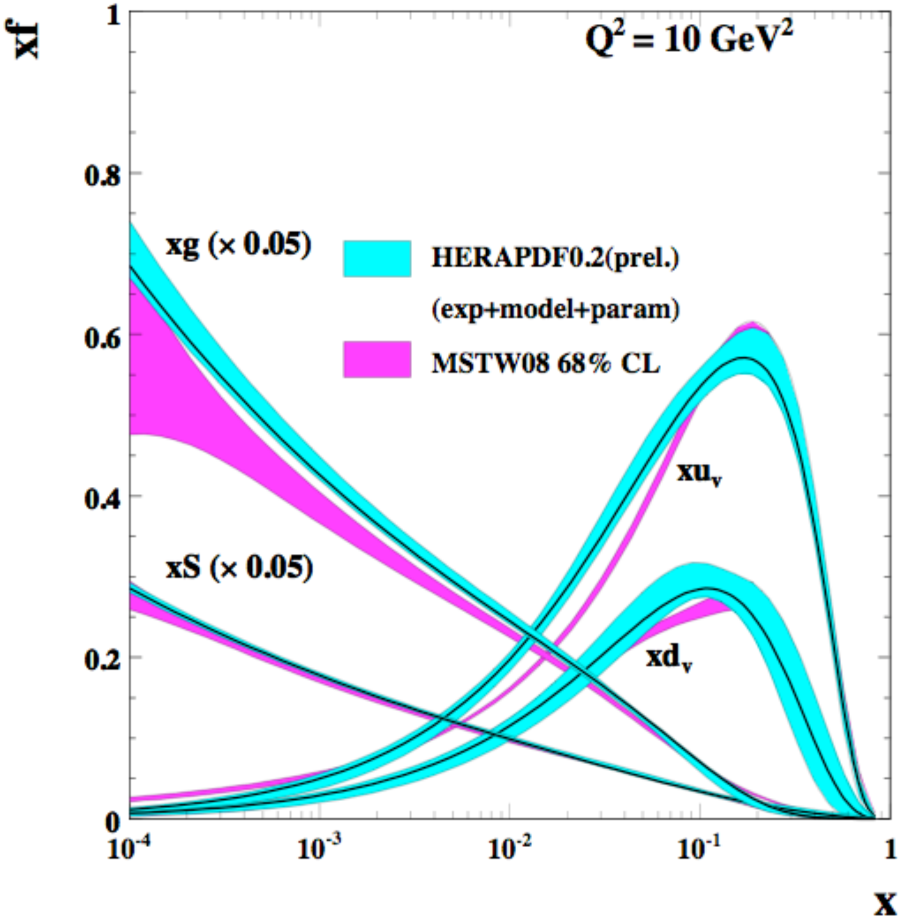
HERAPDF0.2 vs CTEQ/MSTW

- We compare HERAPDF0.2 to the global fits (at 68% CL)
  - The new combined HERA-I data provides a strong constraint on PDFs

CTEQ6.6



MSTW08

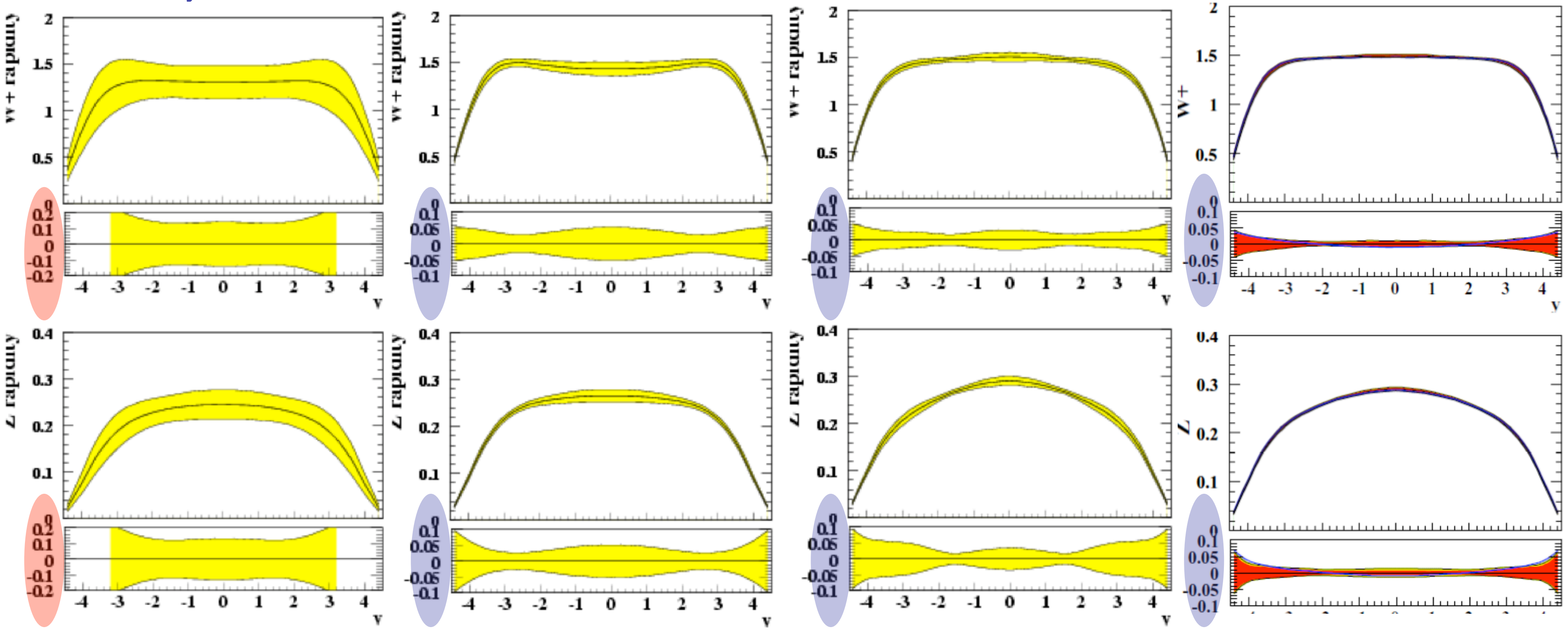


Impact of HERA at the LHC

- Impressive precision on the low-x sea and gluon of the HERAPDF0.2 is relevant for W,Z production at the LHC

W^+, Z rapidities (at 14 TeV!)

Prior any HERA data | only ZEUS data | separate H1 and ZEUS | HERAPDF0.2



  - ➢ The scale for PRIOR any HERA Data is TWO times the scale when any HERA data included!
  - ➢ The errors include only the experimental uncertainties!

✏ Uncertainty at central rapidities when using combined HERA data~1%!

- Inclusion of HERA data shows the tremendous improvement on the predictions for W and Z production at the central rapidity.

Summary

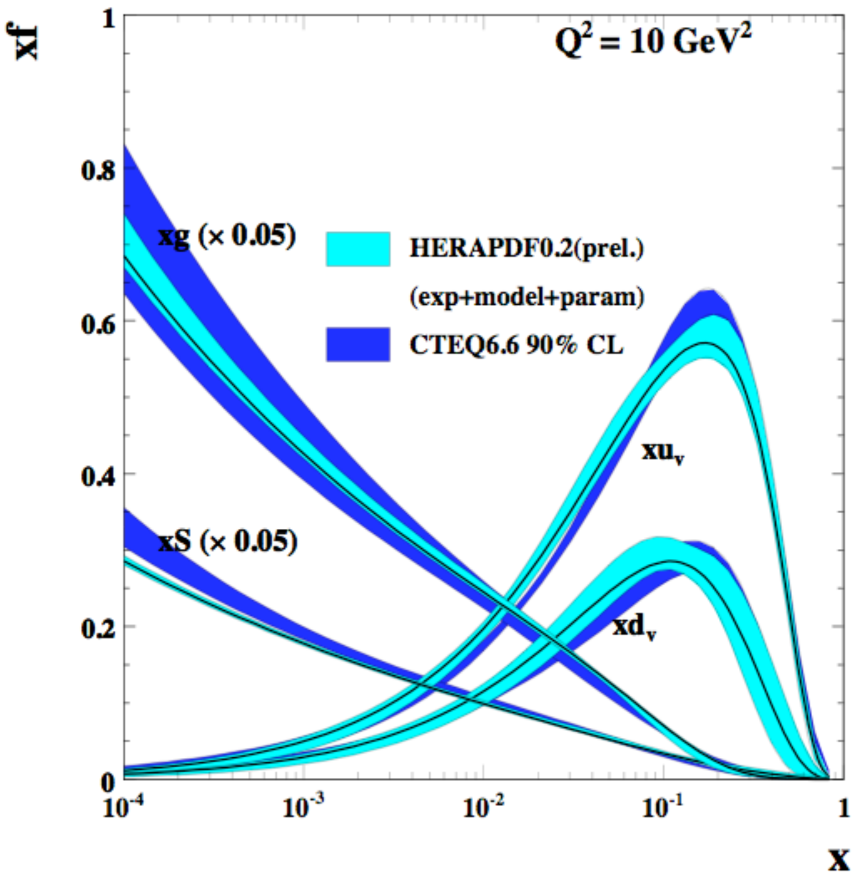
- A model-independent averaging method has been developed to combine the H1 and ZEUS NC and CC cross sections (HERA-I)
  - This results in a consistent data set with significantly reduced systematic and statistical uncertainties
- This combined data is used to perform a new NLO QCD analysis resulting in HERAPDF0.2:
  - Improved theoretical treatment for heavy flavours (TR-VFNS)
  - Model and PDF parametrisation uncertainties are considered
- HERA data is getting ready for precise predictions at the LHC!

Backup

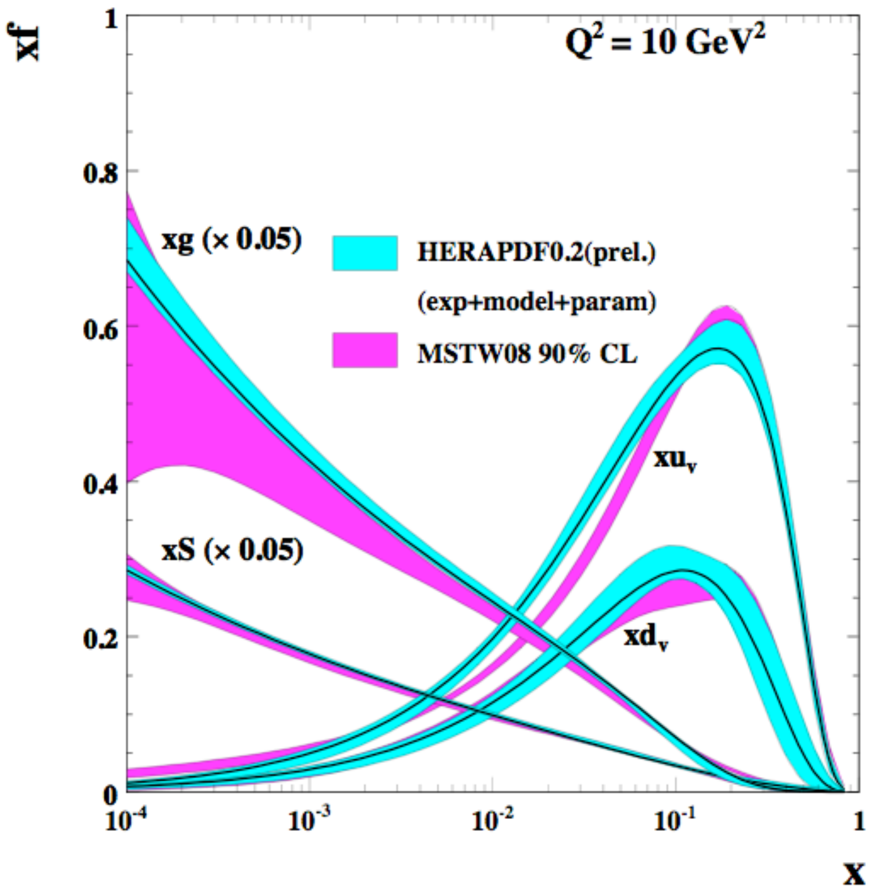
HERAPDF0.2 vs CTEQ/MSTW

- We compare HERAPDF0.2 to the global fits (at 90% CL)
  - The new combined HERA-I data provides a strong constraint on PDFs

CTEQ6.6



MSTW08



Data Combination Strategy

- Swim all points to a common x-Q^2 grid
- Move 820 GeV data to 920 GeV p-beam energy
- Calculate average values and uncertainties
- Evaluate “procedural uncertainties”

  - The grid points are chosen so that the interpolation corrections are minimal
  - Prior combination, H1 and ZEUS data transformed to common x-Q^2 grid using a theoretical calculation

$$\sigma^{e^\pm p}_{NC,CC}(x_{grid}, Q^2_{grid}) = \frac{\sigma^{th,e^\pm p}_{NC,CC}(x_{grid}, Q^2_{grid})}{\sigma^{th,e^\pm p}_{NC,CC}(x, Q^2)} \sigma^{e^\pm p}_{NC,CC}(x, Q^2)$$

Data Combination Strategy

- Swim all points to a common x-Q^2 grid
- Move(1) 820 GeV data to 920 GeV p-beam energy
- Calculate average values and uncertainties
- Evaluate "procedural uncertainties"

(1) Except for data points with y > 0.35

The averaged cross sections have been obtained after having corrected all E_p=820 GeV (with y < 0.35) data points to E_p=920 GeV

CC

$$\sigma_{CC\ 920}^{e^\pm p}(x,Q^2) = \sigma_{CC\ 820}^{e^\pm p}(x,Q^2)\frac{\sigma_{CC\ 920}^{th,e^\pm p}(x,Q^2)}{\sigma_{CC\ 820}^{th,e^\pm p}(x,Q^2)}$$

NC

$$\sigma_{NC\ 920}^{e^\pm p}(x,Q^2) = \sigma_{NC\ 820}^{e^\pm p}(x,Q^2) + \Delta\sigma_{NC}^{e^\pm p}(x,Q^2,y_{920},y_{820}).$$

$$\Delta\sigma e^\pm p_{NC}(x,Q^2,y_{920},y_{820}) = F_L(x,Q^2)\left[\frac{y_{820}^2}{Y_{820}^+} - \frac{y_{920}^2}{Y_{920}^+}\right] + xF_3(x,Q^2)\left[\pm\frac{Y_{820}^-}{Y_{820}^+} \mp \frac{Y_{920}^-}{Y_{920}^+}\right]$$

Experimental Uncertainties

- Uncorrelated uncertainties: ➔E.Tassi's talk
  - Statistical errors
  - Poin-to-point uncorrelated uncertainties:
    - e.g statistical errors due to MC simulations
    - Are added in quadrature to the statistical errors
- Correlated uncertainties:
  - Point-to-point correlated uncertainties
    - e.g. electromagnetic and hadronic energy scale 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
  - largest from photo-production MC and hadronic energy scales

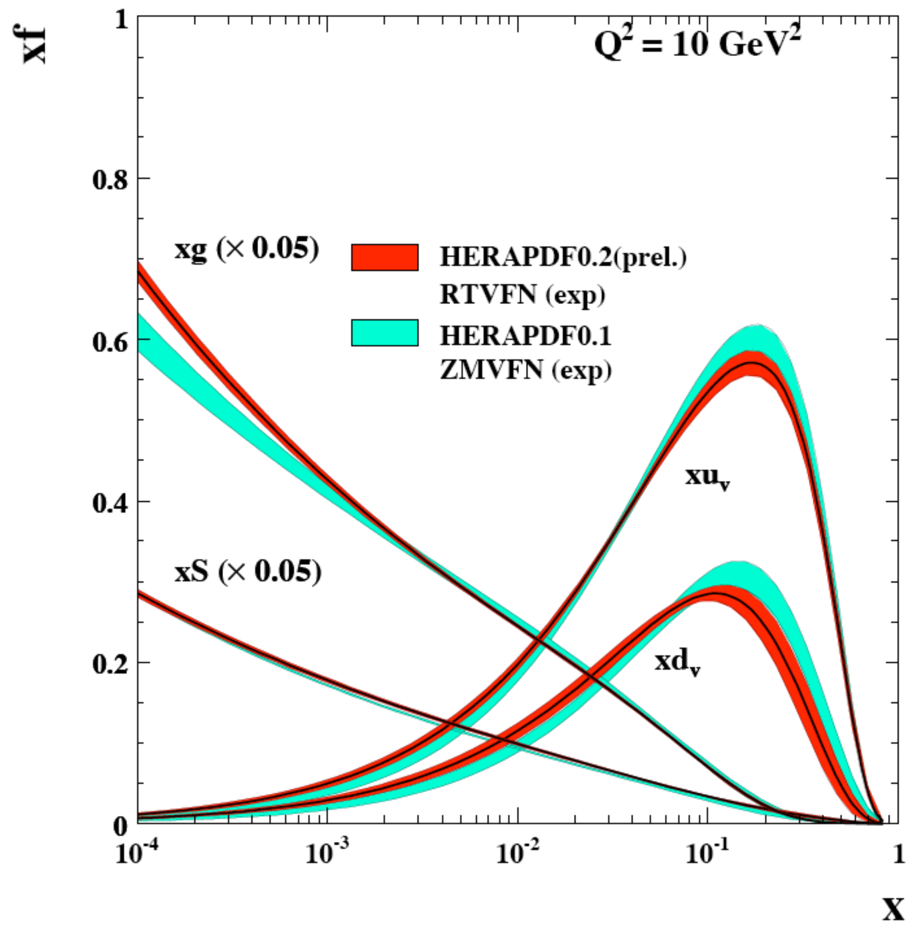
There are 110 systematic errors which are combined in quadrature with the statistical errors and 3 sources of errors from the averaging procedure are offset.

- Small effects observed when errors are treated as correlated

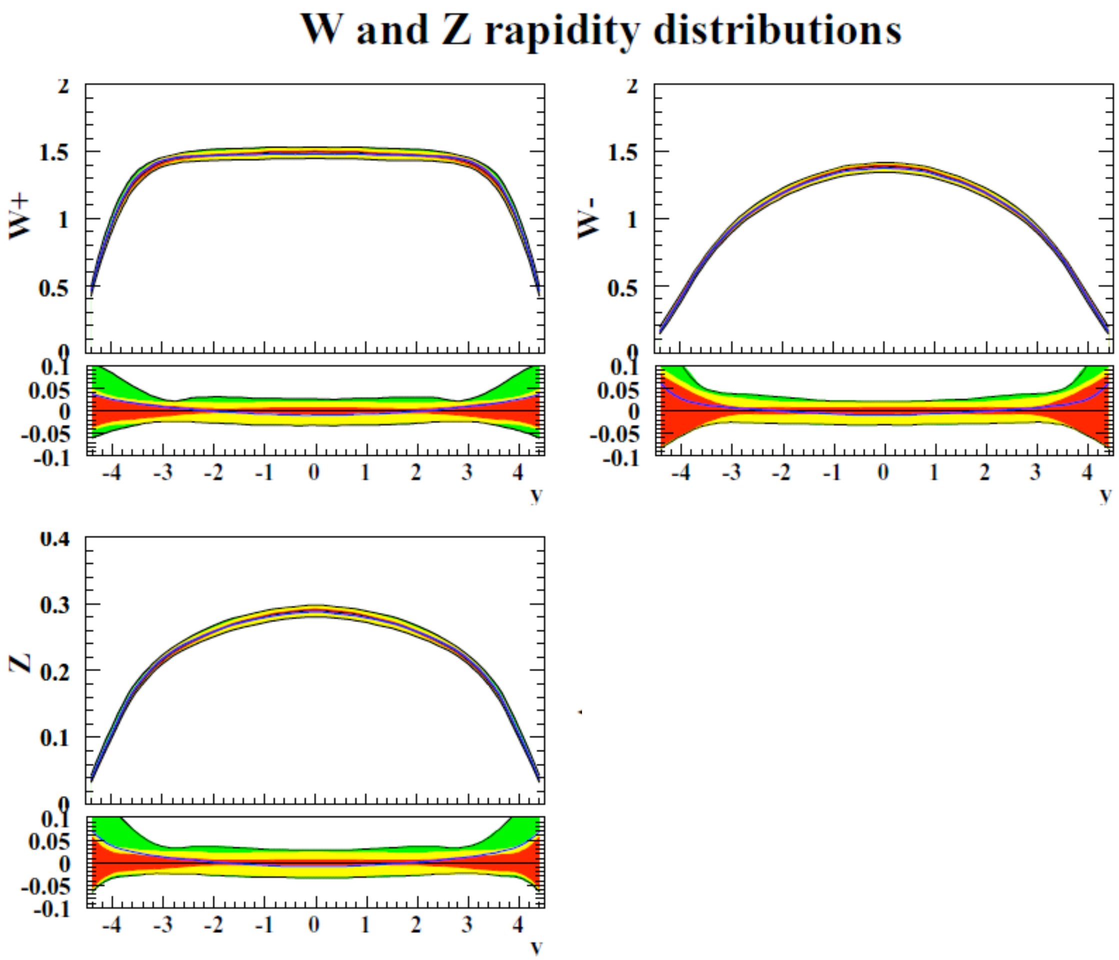
HERAPDF0.1 vs HERAPDF0.2

- For consistency, when comparing the HERA PDF sets only the experimental errors are used:
  - The model uncertainties of the two PDF sets are not identical
  - HERAPDF0.1 did not consider the uncertainty due to PDF parametrisation

- Observations:
  - Errors are smaller for HERAPDF0.2
  - d_{val} is softer
  - Gluon is steeper:
    - This is expected due to the heavy flavour treatment
      HERAPDF0.1 - massless quarks (ZM-VFNS)
      HERAPDF0.2 - massive quarks (TR-VFNS)



Include all PDF uncertainties



Include all PDF

uncertainty ~2%

Uncertainties:

Data: red

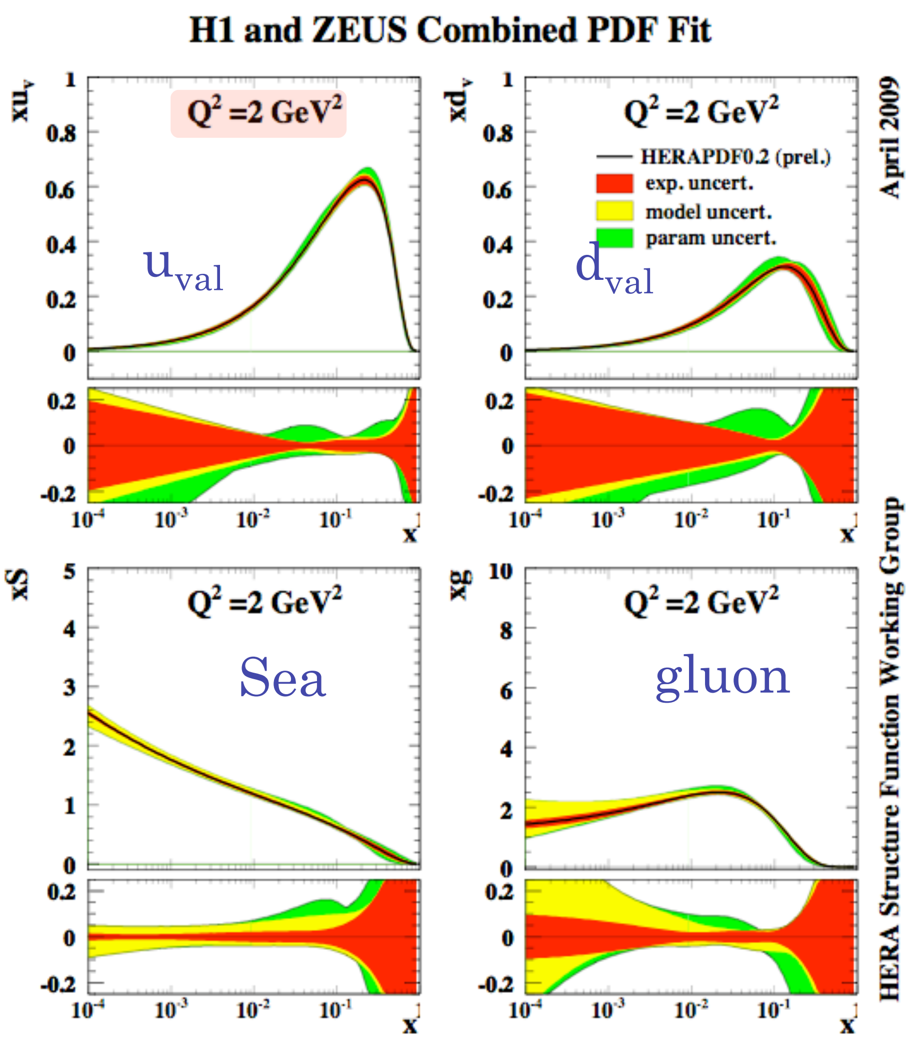
Model : yellow

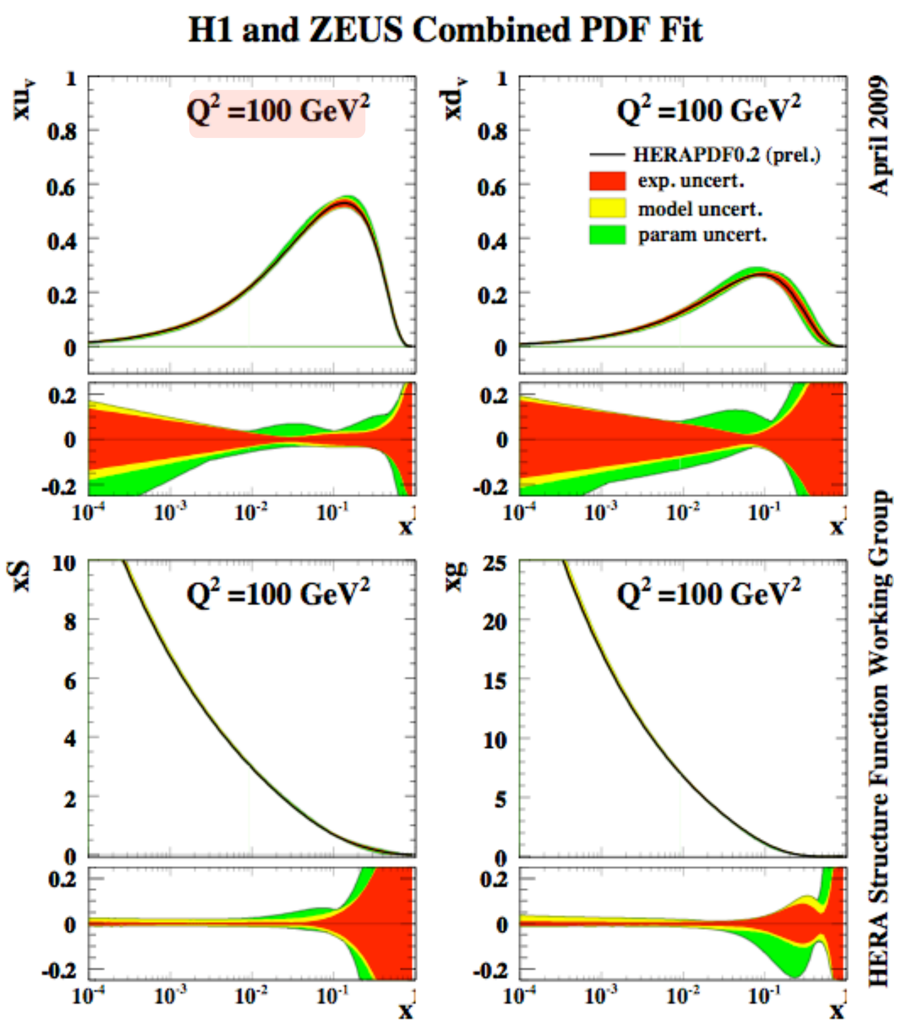
Param.: green

Note the increase in uncertainty at large |rapidity| <> large *x*

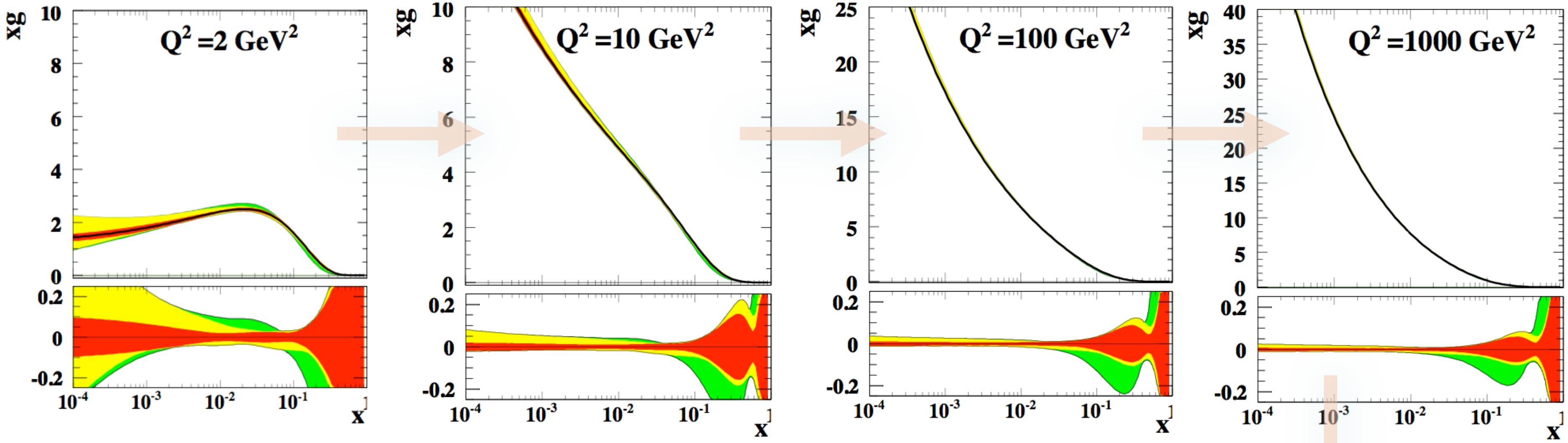
HERAPDF0.2 for different scales

- At the starting scale gluon is valence like
  - Q_0^2, Q^2_{min} dominate the model uncertainty of gluon and valence PDFs
- PDF parametrisation uncertainty dominates valence PDFs and high x region

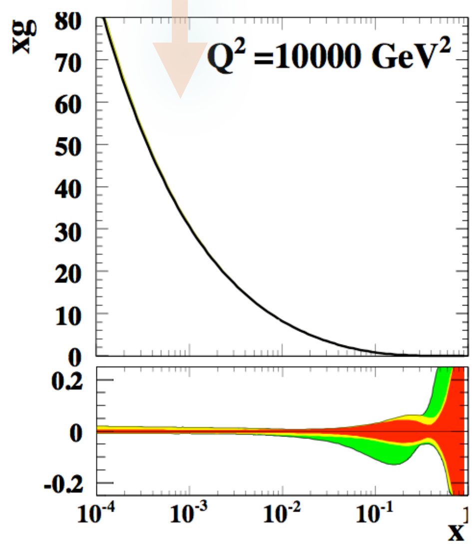




Evolution of gluon with Q^2



- Near the starting scale gluon is valence like
  - The model uncertainties are large in low x region
    - Mostly due to Q_0^2 variations
  - The PDF param. uncertainty dominates high x



- Impressive precision at higher Q^2!