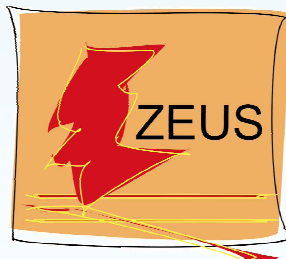


# Combined HERA DIS data and PDF fits

New Trends in HERA Physics, Ringberg'08

**Claire Gwenlan** (University of Oxford, STFC Fellow)  
on behalf of the **HERA Structure Functions Working Group**

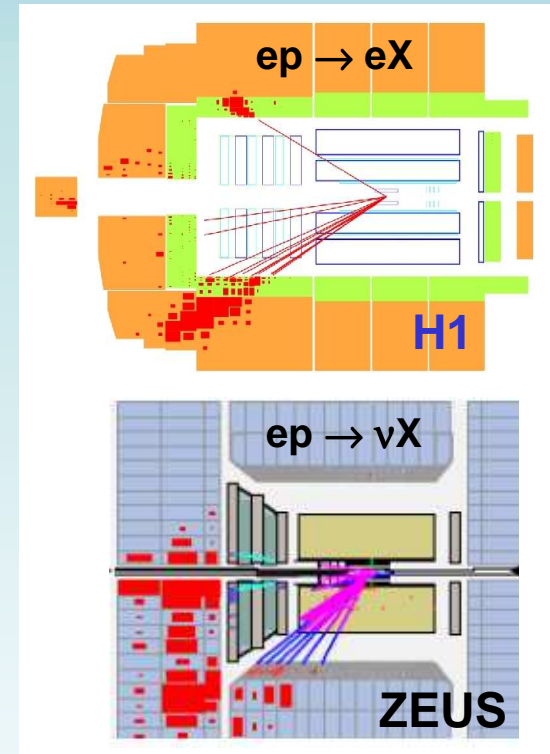


## Outline

- Introduction
- Combined HERA DIS data
- NLO QCD fit to the data
- Summary

# Motivation

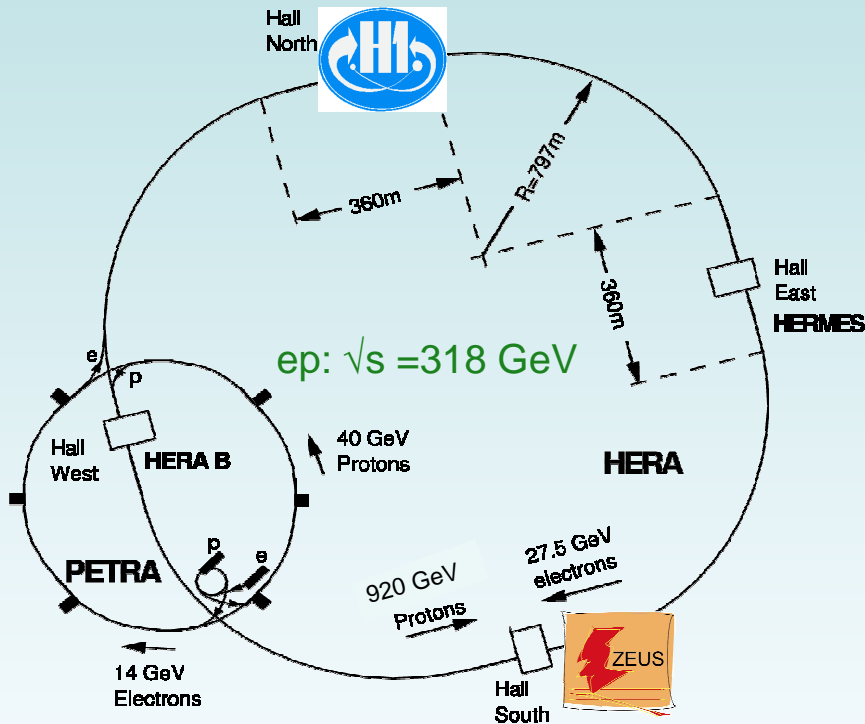
- HERA collider has provided a **wealth** of  $e^\pm p$  data (from 94-07)
- measurements of **Deep Inelastic Scattering (DIS)**, made by **H1** and **ZEUS**, **crucial** for **constraining quark** and **gluon densities** in the **proton**
- analysis of **HERA-I** data now (almost) **complete** and best precision **HERA-II** measurements coming soon ...



**NOW:** want to **maximise** impact of HERA by **combining** H1 and ZEUS data → **obtain best precision cross sections** → leading to most precise extractions of the proton parton density functions (PDFs)

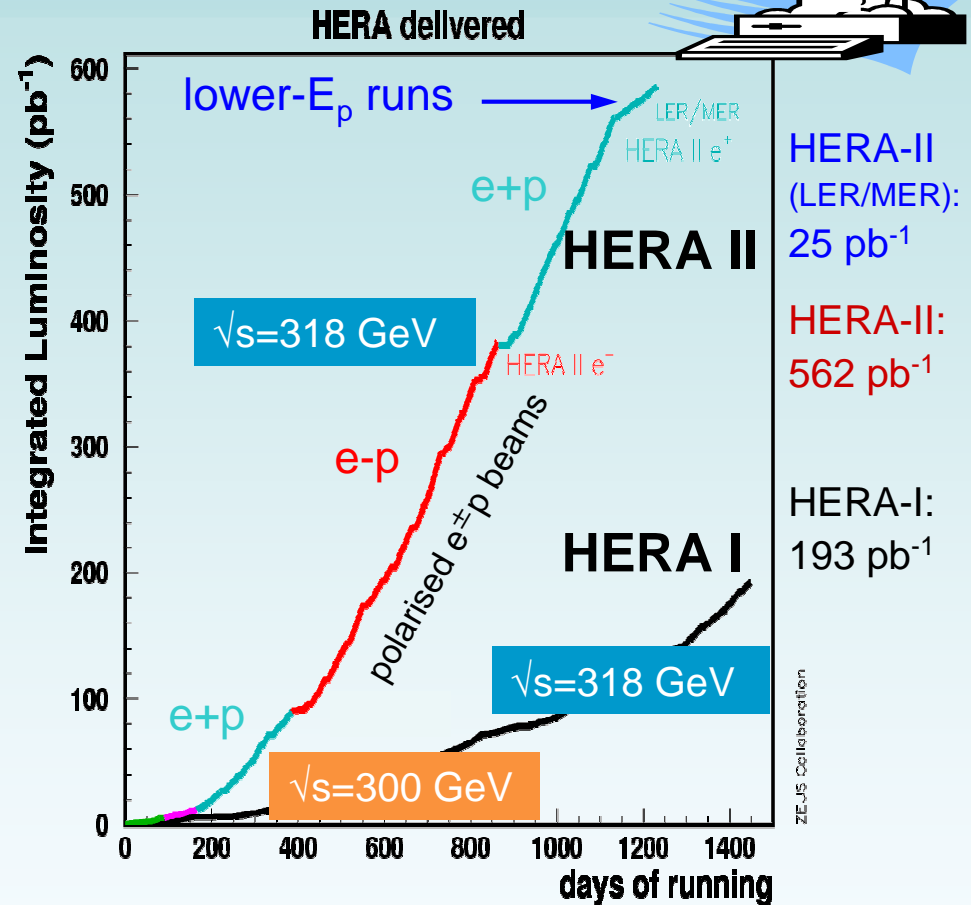
# HERA collider

HERA: world's **only** ep collider



HERA ep data collected per exp.:

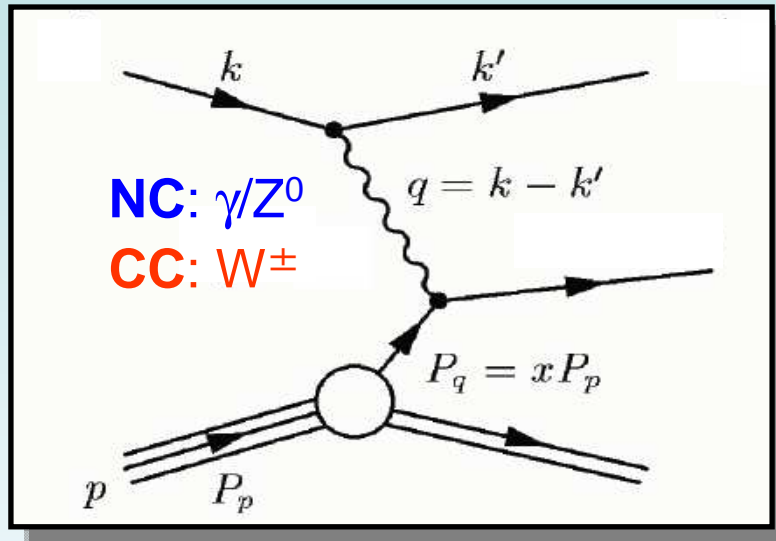
	e <sup>+</sup> p	e <sup>-</sup> p
HERA-I	~100 pb <sup>-1</sup>	~20 pb <sup>-1</sup>
HERA-II	~200 pb <sup>-1</sup>	~200 pb <sup>-1</sup>



**HERA** laid to rest summer'07

# Deep Inelastic Scattering

Processes: **Neutral Current (NC)**:  $ep \rightarrow eX$ ; **Charged Current (CC)**:  $ep \rightarrow \nu X$



## Kinematic Variables:

- 4-momentum transfer (“resolution”):  
 $Q^2 = -q^2 = -(k - k')^2$
  - Bjorken scaling variable:  $x = Q^2 / 2p \cdot q$
  - inelasticity:  $y = p \cdot q / p \cdot k$
- related via  $s$ :  $Q^2 = sxy$   
 [where  $\sqrt{s}$  = COM energy:  $s = (k + p)^2$ ]

**NC**: “reduced” cross section:

$$\tilde{\sigma}^\pm = \frac{d^2\sigma^\pm}{dx dQ^2} \frac{Q^4 x}{2\pi\alpha^2 Y_+} = \tilde{F}_2^\pm \mp \frac{Y_-}{Y_+} x \tilde{F}_3^\pm - \frac{y^2}{Y_+} \tilde{F}_L^\pm$$

valence and sea quarks  
 [gluon via scaling violations]

valence quarks

gluon

**CC**: similar decomposition, but **different quark combinations** accessed in  $e^+p$  or  $e^-p \rightarrow$  **flavour sensitive**

# Combined HERA DIS data

# Idea:

**AIM:** combine **H1** and **ZEUS** inclusive NC and CC DIS data

specifically: “reduced” DIS cross sections; HERA I data only (so far!)

some details:

- combination method (developed by A. Glazov) uses an iterative  $X^2$  minimisation → takes full account of correlated systematics
- different technologies of the **H1** and **ZEUS** detectors exploited to “cross-calibrate”, and hence improve the systematic uncertainties
- **key assumption:** the two experiments are measuring the **same** cross section at the **same** kinematic point

**Presented here:** preliminary results, as submitted to Lepton-Photon '07

# NC and CC data sets

1153 data points in total;  $Q^2 > 1.5 \text{ GeV}^2$

Based on published (as in summer'07) NC and CC data from HERA I:

input data: **published HERA-I cross sections [total lumi.:  $\sim 240 \text{ pb}^{-1}$ ]**

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	1.5	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	$e^+p \sqrt{s} = 319 \text{ GeV}$

NB: H1 minimum bias ( $Q^2 < 12 \text{ GeV}^2$ ) moved up by 3.4% after re-analysis of luminosity

# NC $e^+p$ example

$$\sigma_r^{e^+p \rightarrow e^+X} = F_2 - \frac{y^2}{Y_+} F_L \mp \frac{Y}{Y_+} xF_3$$

**EXAMPLE** data set for averaging:  **$e^+p$  NC DIS** from **H1** and **ZEUS**

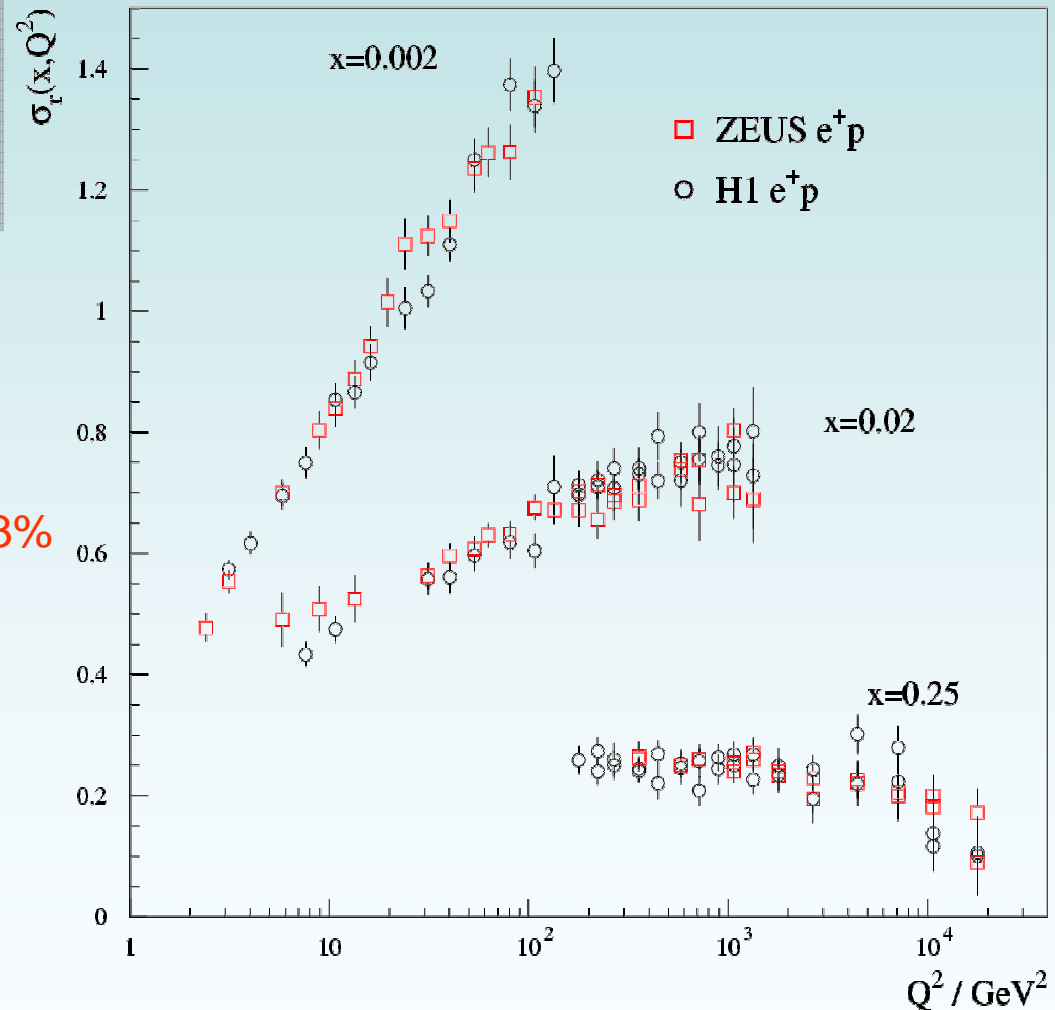
precise measurements from **two** experiments:-

**uncertainties:**

- $Q^2 < 100 \text{ GeV}^2$  :  $\delta_{\text{stat}} < 1\%$ ,  $\delta_{\text{syst}} < 3\%$
- $Q^2 > 1000 \text{ GeV}^2$  :  $\delta_{\text{stat}} > \delta_{\text{syst}}$

**these data** (plus others, as listed on previous slide) to be **combined** into **average** “HERA data set”

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



HERA Structure Functions Working Group



# HERA combination method

## Procedure (in a nutshell):

- i. move all data points to **common** ( $x, Q^2$ ) grid
- ii. transform data to **common** proton beam energy
- iii. calculate **average values** and **uncertainties**
- iv. evaluate uncerts. due to **combination procedure**

further details on next slides →

# Common (x,Q<sup>2</sup>)

move all data points to **common** (x,Q<sup>2</sup>) grid

- essentially: **H1** binning in **x**; **ZEUS** binning in **Q<sup>2</sup>**
- shift measured data by **simple interpolation** using **H1PDF2k**:

$$\sigma_{ep}^{meas}(x_{grid}, Q_{grid}^2) = \frac{\sigma_{ep}^{th}(x_{grid}, Q_{grid}^2)}{\sigma_{ep}^{th}(x, Q^2)} \sigma_{ep}^{meas}(x, Q^2)$$

**NB:** sensitivity of interpolation to choice of PDF checked using ZEUS-Jets:

- **NC shift factors** agree to within a few permille;
- **CC** to <2% (i.e. much less than statistical uncertainties)

# Beam energy correction

transform data to  $E_p = 920$  GeV beam energy:

**simple** beam energy correction for **CC** data:

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

**additive** beam energy correction performed for **NC** data:

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

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

**systematic uncertainty** estimate: compare  $F_L=0$  and  $F_L=F_L$  (H1PDF2k)  
- up to 5% at large  $y$  → assigned as a correlated “procedural” systematic

# Method

**A. Glazov** [DIS'05, HERA-LHC ws]

HERA averaging [uses **Lagrange Multiplier** (or “**Hessian**”) **method**]:  
**model-independent\*** **combination** of H1 and ZEUS data, prior to  
QCD analysis, taking **full account of correlated systematics**

\*only theoretical input to procedure:

**H1** and **ZEUS** measure the **same** cross sections at the **same**  $x, Q^2, y$   
[i.e. we assume physics is the same, either side of the HERA ring!!!]

this gives a **strong constraint** → each experiment **calibrates** the other  
→ works well since **systematic sources** rather **different** between experiments

method minimises the following **probability ( $X^2$ ) distribution** →

# $\chi^2$ definition

$\equiv$  standard average if  $\Delta\alpha_j=0$

$\chi^2$  for single data set:

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

$M^i$  : **measured** central values

$\sigma_i$  : **statistical** and **uncorrelated systematic** uncertainties of M

$\sigma_{\alpha_j}$  : **correlated systematic** uncertainties

$\frac{\partial M^i}{\partial \alpha_j}$  : sensitivity of datum i to systematic uncertainty j

$M^{i,\text{true}}$  : fitted **combined H1-ZEUS data** [i.e. the “true” HERA values]

$\Delta\alpha_j$  : fitted **shifts of correlated uncertainties**

It's a **cross-calibration** of correlated systematics between different data sets

# X<sup>2</sup> definition

X<sup>2</sup> for single data set:

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

## CAVEAT:

- in principle, a nice simple X<sup>2</sup>, which allows minimisation by **linear equations**
  - **unbiased** for “**additive**” uncertainties (those **independent of central value**)
  - BUT for **cross sections**, many uncertainties are “**multiplicative**”  
(ie. **proportional to the central value**)
- **introduces bias towards smaller averages:** i.e. a smaller M<sup>i</sup> will have a smaller relative uncertainty and hence give a smaller X<sup>2</sup>

bias can be avoided by **modifying the definition** of the X<sup>2</sup> →

# Revised $\chi^2$ definition

$\chi^2$  for single data set:

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

**minimisation** is now **non-linear** → use an **iterative procedure**:

1. minimise original  $\chi^2$  to find an **initial approximation**  $\{M^{i,\text{true}}\}$
  2. translate **multiplicative** uncertainties to **additive**:  $\sigma_i \rightarrow \sigma_i (M^{i,\text{true}}/M^i)$
  3. repeat step 1.
- **convergence** is usually after two iterations

$\text{cov}(M^{i,\text{true}}, M^{j,\text{true}})$  gives the **error matrix** for the combined data

[NB. full  $\chi^2$  is the **sum** over all  $\chi_{\text{exp}}^2$ ]

# Uncertainties

## treatment/prescription:

- **statistical** and **uncorrelated systematics** combined in **quadrature** to give **total point-to-point uncorrelated uncertainty** ( $\sigma_i$ )
- treatment of **correlated** systematic uncertainties:
  - correlated **between** data sets of **same experiment**:
    - normalisation (clearly treat as **multiplicative**)
    - others (e.g. energy scale): **additive** or **multiplicative**? **Debatable!!!**  
**extremes:** treat **all** as “additive” and **all** as “multiplicative”  
→ assign difference as additional correlated “**procedural**” uncert.
  - correlations **between** experiments? (next slide)

in total: **43 sources** of correlated systematics from the data



# Correlations between exps.?

consideration of correlations between H1 and ZEUS:

- correlations **between** experiments?
  - **similar methods** for MC simulations, calibration techniques, ...
  - some correlations should exist

identified twelve possible uncertainties of **common origin**:

**CHECK:** take all pairs as **correlated** or **uncorrelated** in turn

→ calculate  $2^{12}-1$  alternative averages → determine **deviations** from **central value**

→ **mostly negligible**; largest differences arise from **hadronic energy scale** and **photoproduction background**

→ deviations from these two sources treated as “**procedural**” uncertainties

# Procedural uncertainties

## 4 sources of uncertainty from the combination procedure

### summary of sources:

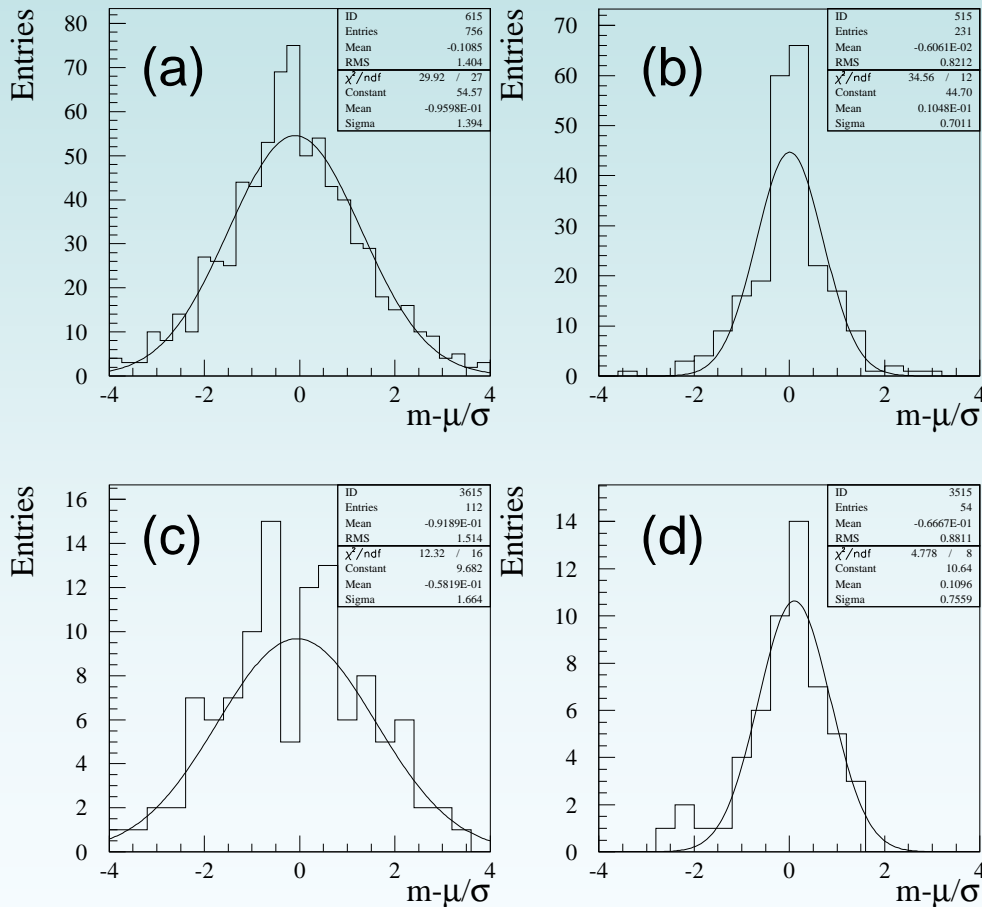
- **centre-of-mass energy correction**
  - mostly at permille level, but up to 5% at largest  $y$ ,  $Q^2 \sim 10 \text{ GeV}^2$   
[note: if only data with  $y < 0.35$  transformed in centre-of-mass energy (as in most recent combinations), this uncertainty reduces to  $< 0.5\%$ ]
- **additive versus multiplicative systematics**
  - $< 1\%$  except at large  $x, Q^2$
- correlations **between** experiments:
  - **hadronic energy scale**: 1% at low  $y$
  - subtraction of **photoproduction** background: 1-2% at large  $y$

these uncertainties are added to the averaged data points

[at few permille level across most of the kinematic plane, with few exceptions]

# Fit quality

$$(M - M^{\text{true}}) / \sigma_i$$



**1153 individual NC and CC measurements from HERA I averaged to 554 points**

resulting **good quality** of fit:

$$\chi^2/\text{dof} = 510/599$$

	pulls	
	mean	sigma
(a) NC e+p	-0.09	1.4
(b) NC e-p	0.01	0.7
(c) CC e+p	-0.05	1.7
(d) CC e-p	0.1	0.8

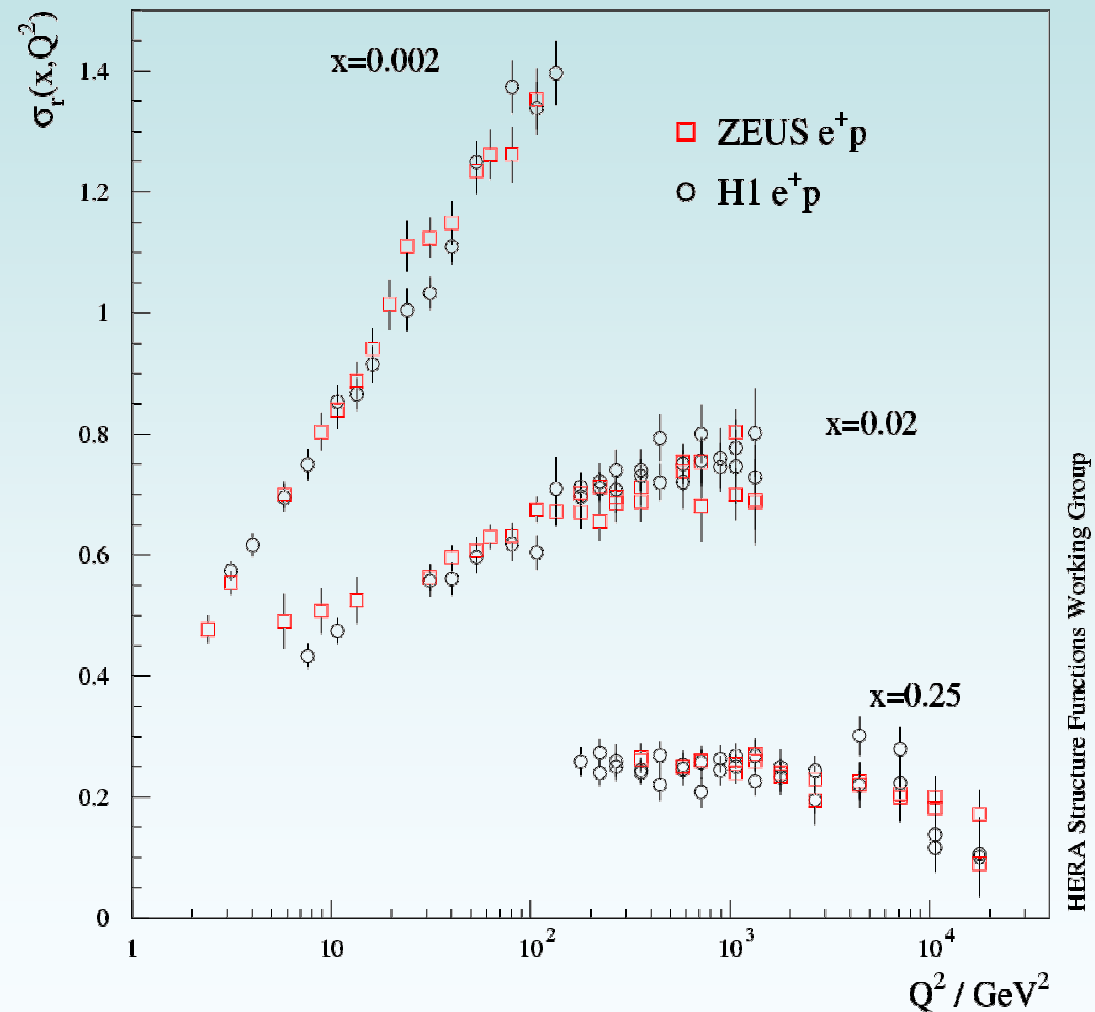
→ **no significant tensions** seen across kinematic plane

**Note:** 43 systematic uncertainties from data and 4 from combination procedure

# Results (i): NC e<sup>+</sup>p

**REMINDER:** individual measurements from **H1** and **ZEUS** [zoom in on three example x values]

HERA I e<sup>+</sup>p Neutral Current Scattering - H1 and ZEUS

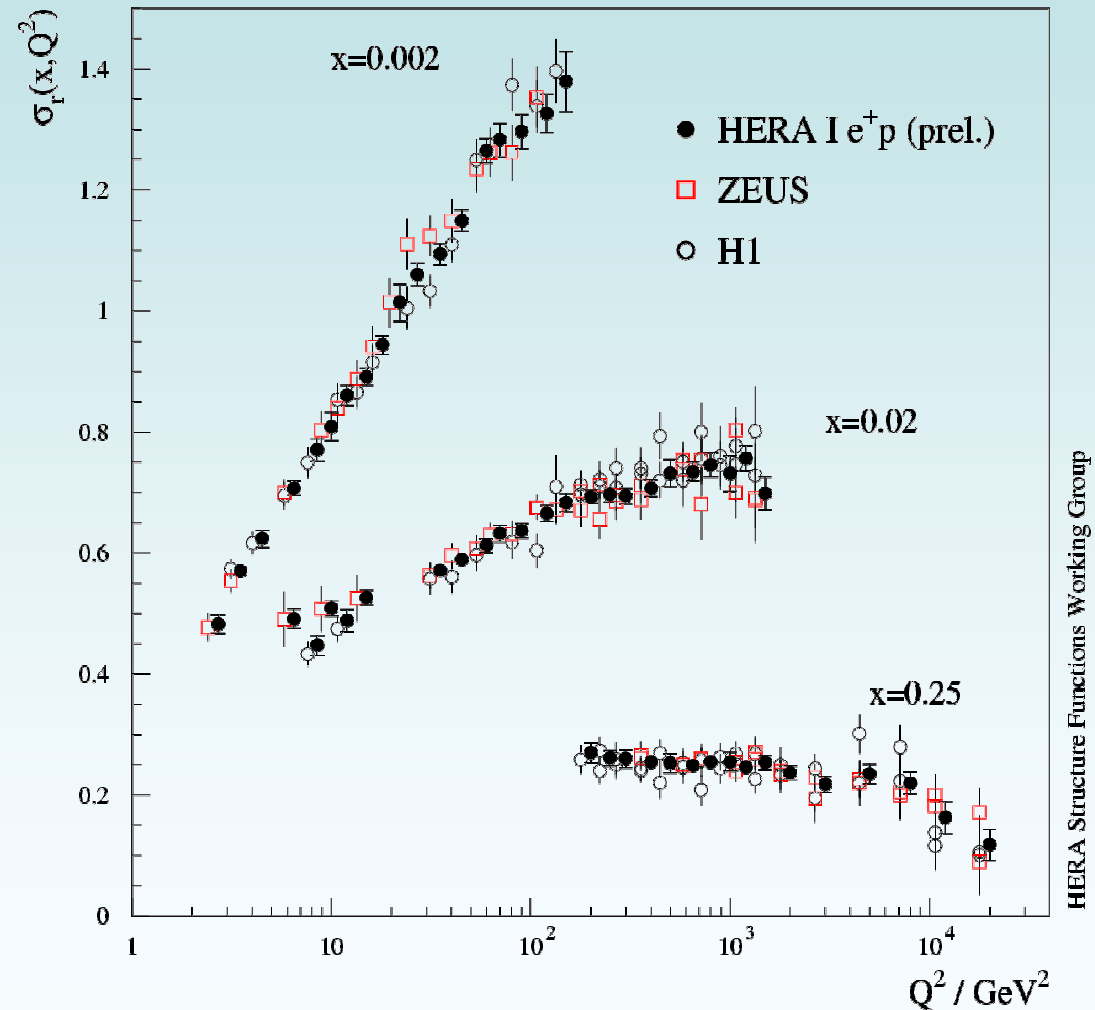


# Results (i): NC $e^+p$

**REMINDER:** individual measurements from **H1** and **ZEUS** [zoom in on three example  $x$  values]

Compared to **combined data-set** (solid points)

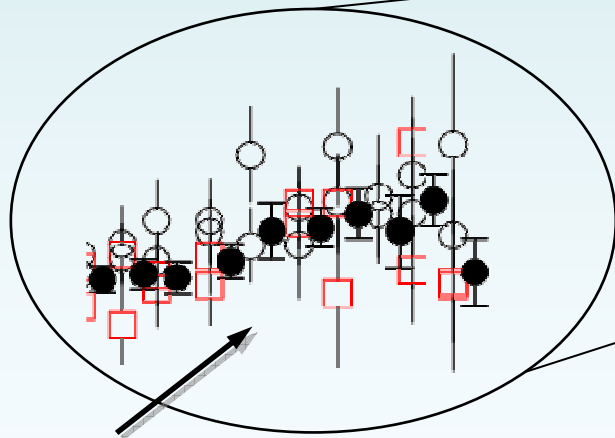
HERA I  $e^+p$  Neutral Current Scattering - H1 and ZEUS



# Results (i): NC e<sup>+</sup>p

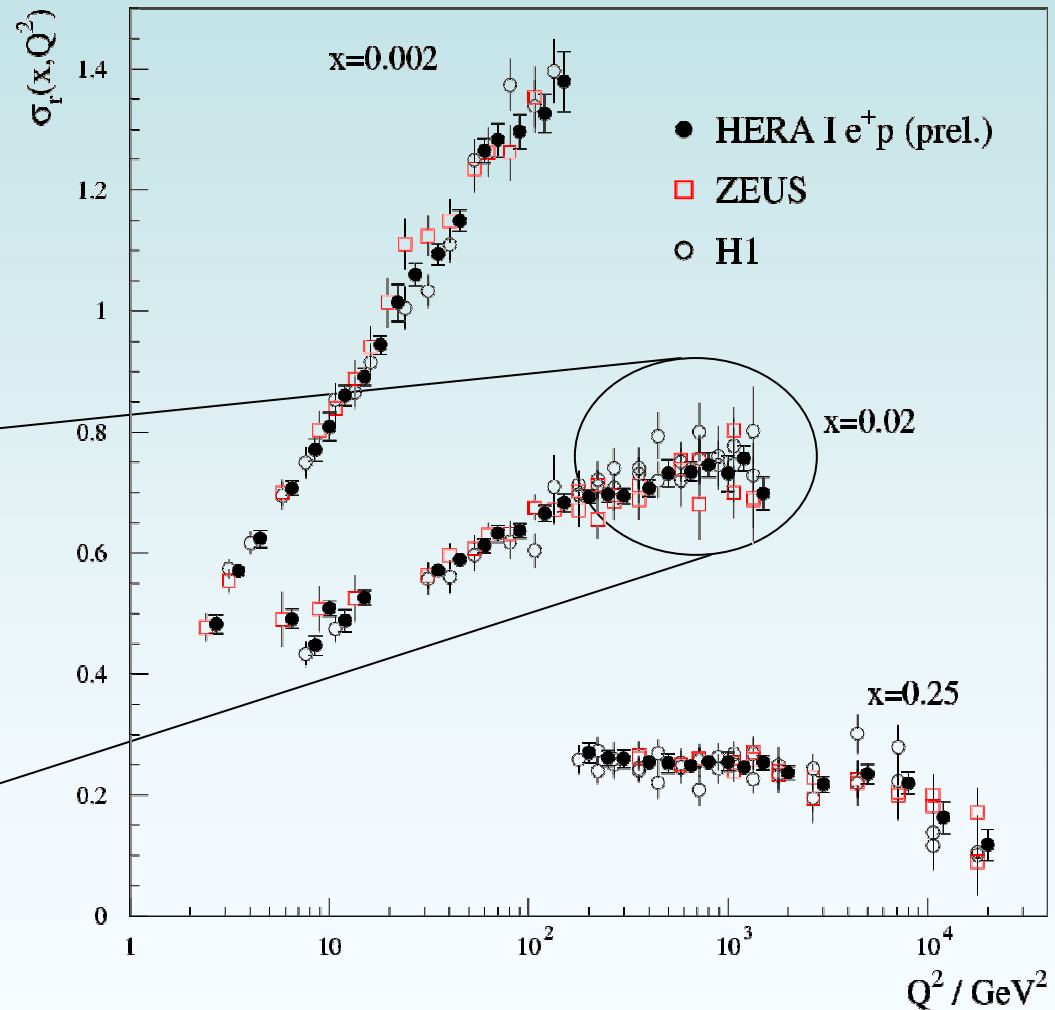
**REMINDER:** individual measurements from **H1** and **ZEUS** [zoom in on three example x values]

Compared to **combined data-set** (solid points)



better than naively-expected improvement from statistics:  
"cross-calibration"

HERA I e<sup>+</sup>p Neutral Current Scattering - H1 and ZEUS



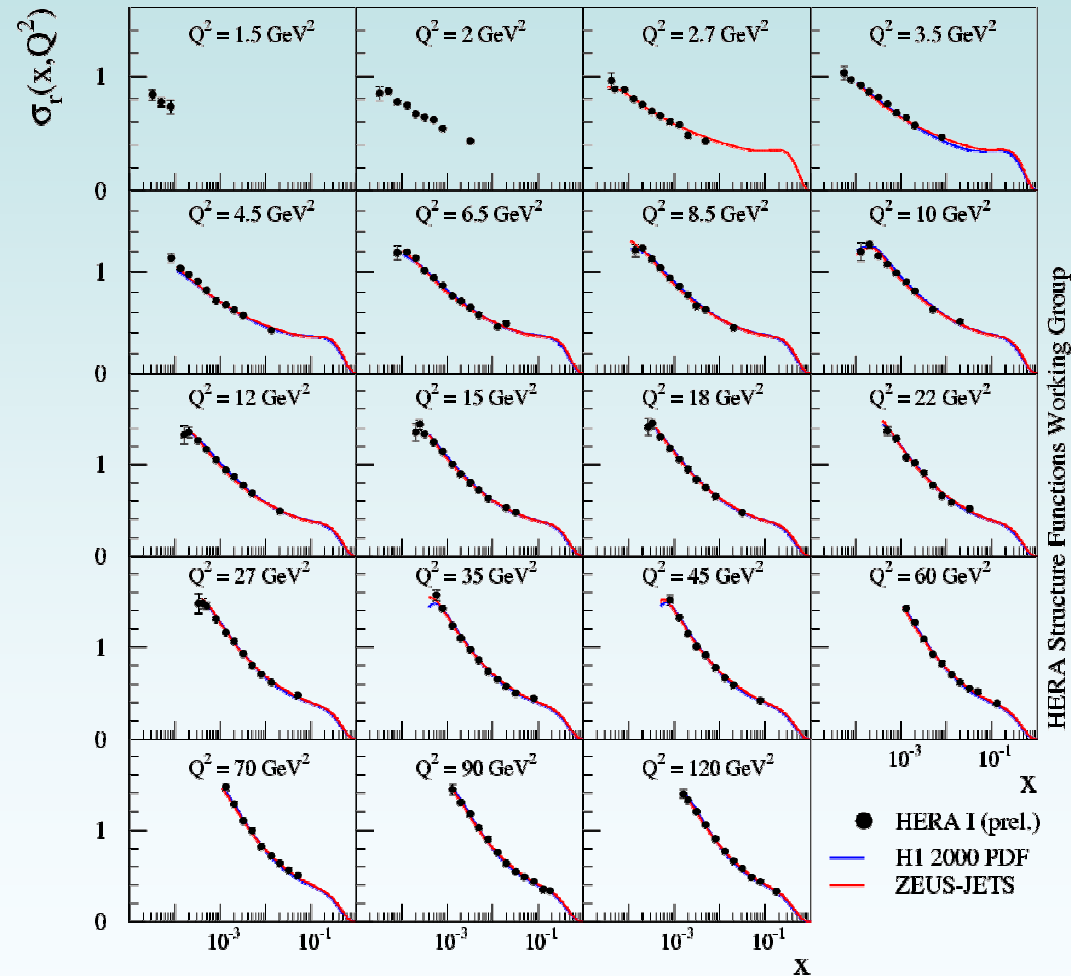
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# Results (ii): NC e<sup>+</sup>p

NC e<sup>+</sup>p [at low Q<sup>2</sup>]:

combined data compared to published **H1** and **ZEUS** PDF fits to (their own) data from **HERA I**

HERA I e<sup>+</sup>p Neutral Current Scattering - H1 and ZEUS

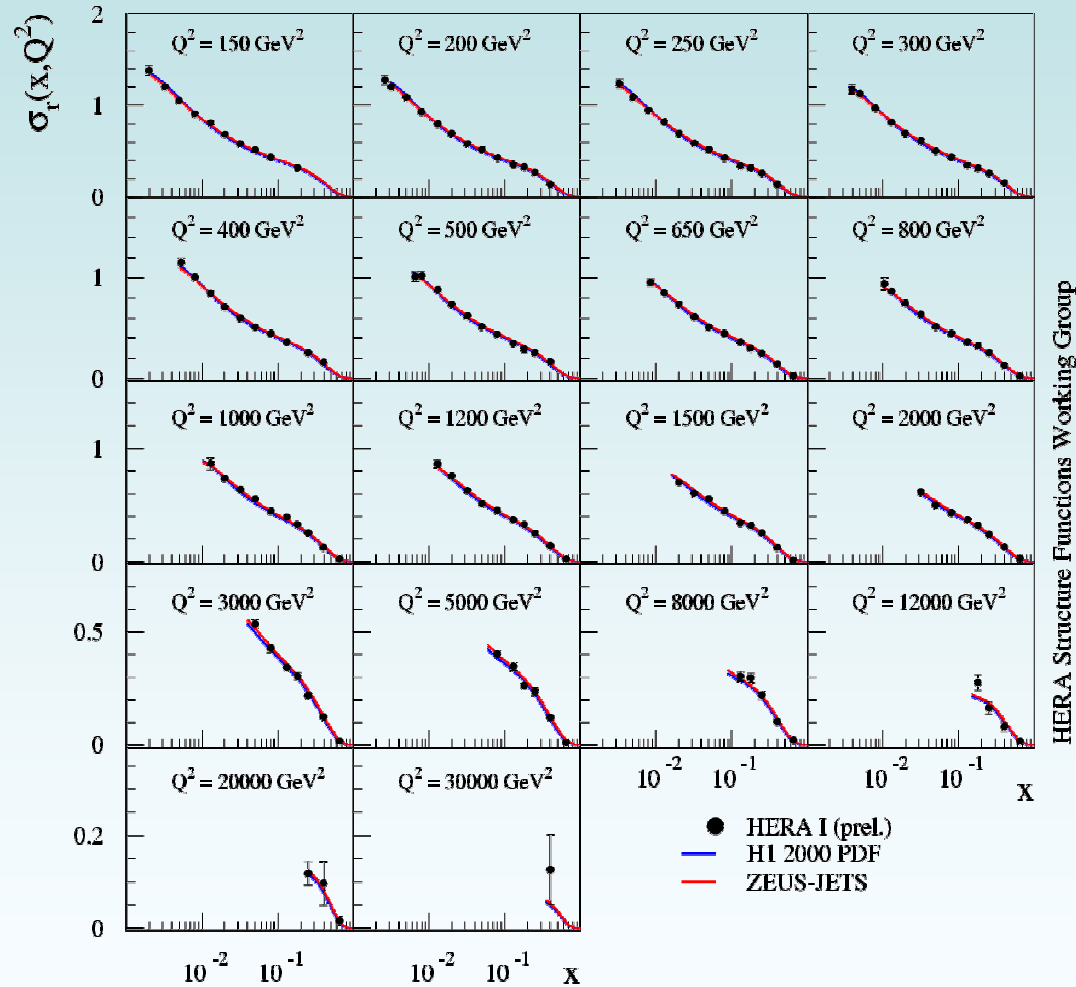


# Results (iii): NC e<sup>+</sup>p

NC e<sup>+</sup>p [at high Q<sup>2</sup>]:  
combined data compared  
to published **H1** and **ZEUS**  
PDF fits to (their own)  
data from **HERA I**

[e-p equivalent in backups]

HERA I e<sup>+</sup>p Neutral Current Scattering - H1 and ZEUS





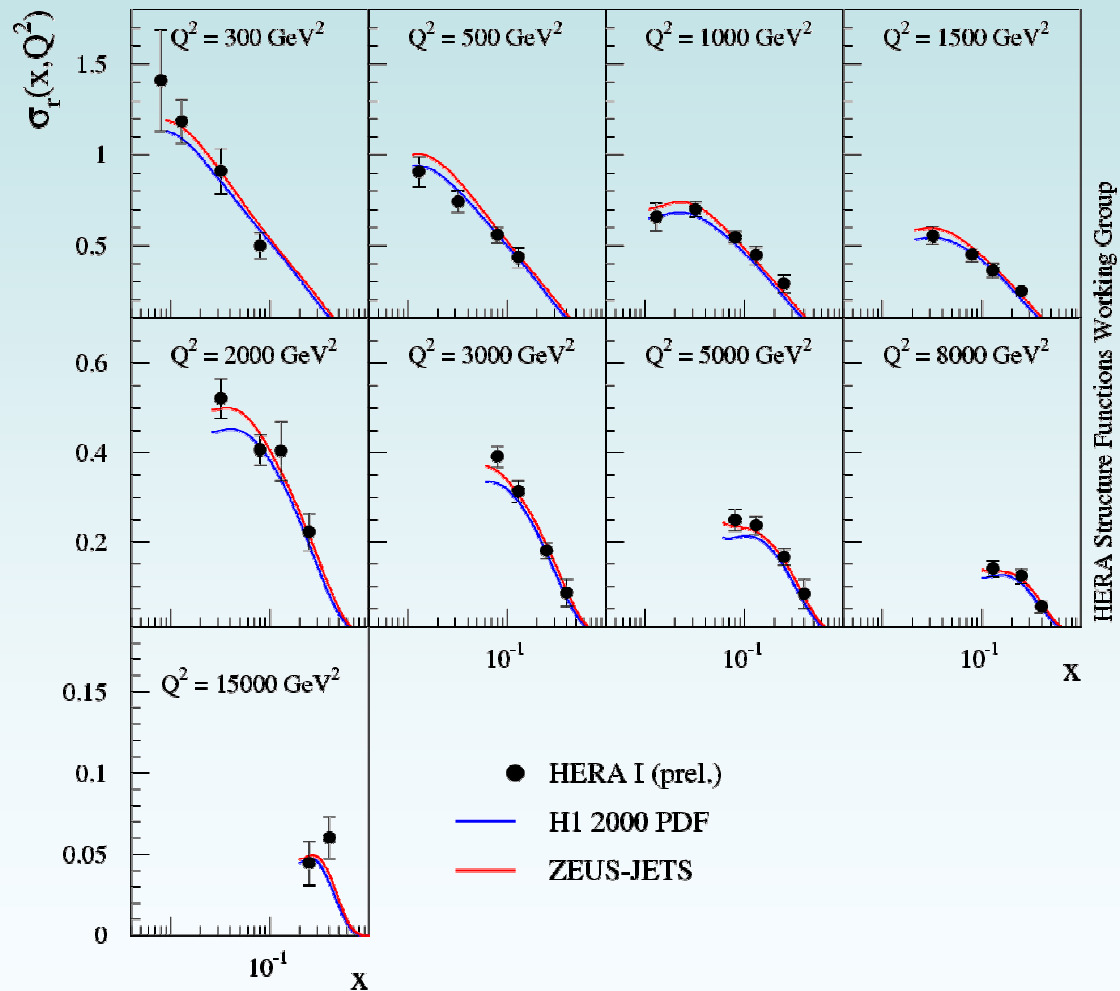
# Results (iv): CC e<sup>+</sup>p

## CC e<sup>+</sup>p:

**combined data** compared to published **H1** and **ZEUS** PDF fits to (their own) data from **HERA I**

[e-p equivalent in backups]

HERA I e<sup>+</sup>p Charged Current Scattering - H1 and ZEUS



# Results (cont.)

## some final comments on the results

- all uncertainties **within** 1 sigma of original, published values [except normalisation of H1 low- $Q^2$  (96-97) → moved up by 1.6 sigma]
- almost **all systematics improved**. most significantly:
  - **H1** backward calorimeter energy scale:- factor of 3
  - **ZEUS** forward hadronic energy modelling:- factor of 4
- overall **precision improved**
  - $Q^2 < 12 \text{ GeV}^2$ : H1 and ZEUS separately ~2-3%; combined <2%
  - medium- $Q^2$ : precision reaches 1.5%
  - high- $Q^2$ : 10% level [statistics important here]

systematics now **smaller** than statistical uncerts. over most  $x, Q^2$

# **QCD fit to the combined data**

# HERA NLO QCD fit

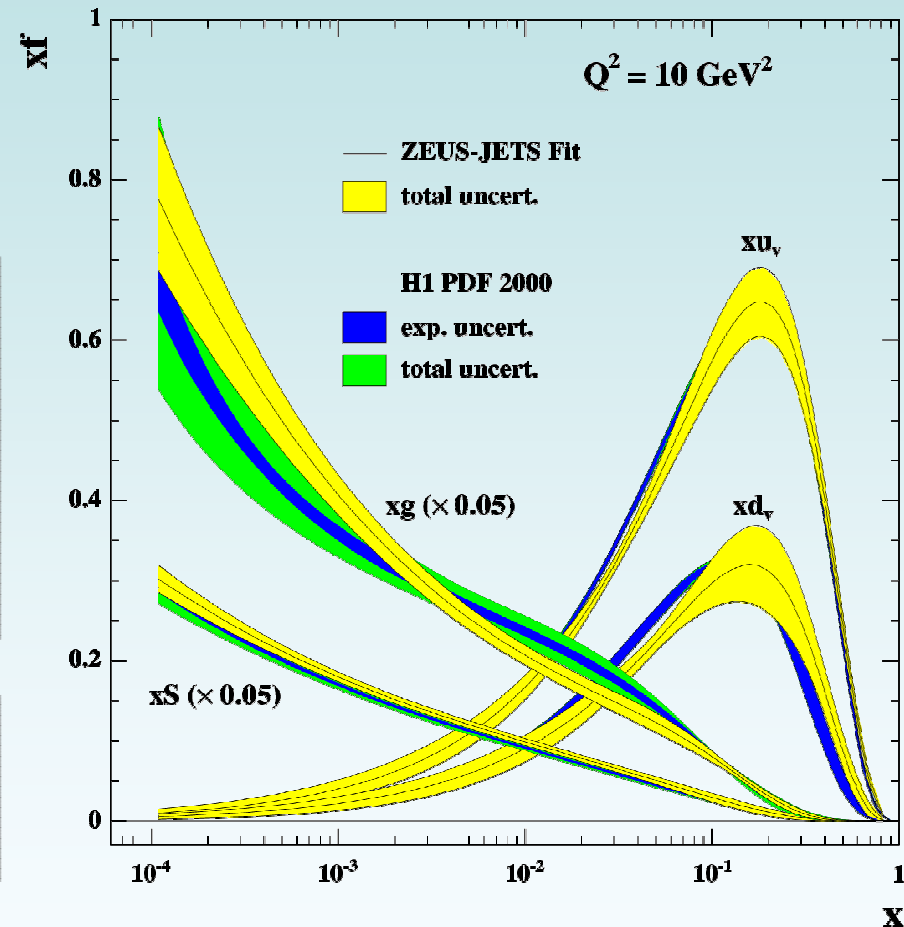
**Previously:** H1 and ZEUS have performed **NLO QCD fits** to their own HERA-I data ... →

**NOW:**

→ the **combined HERA-I data** have been used as **sole input** for a **new HERA NLO QCD fit** to extract the **proton PDFs**

**AIM:** precision extraction of PDFs using HERA data alone!!!

published HERA-I PDFs



**Presented here:** preliminary results, as submitted to ICHEP'08

# HERA PDF parameterisation

Choose form of PDF parameterisation at  $Q_0^2 = 4 \text{ GeV}^2$

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

normalisation      low-x behaviour      high-x behaviour      polynomial term  
 (terms added until no further  $X^2$  advantage)

partons parameterised: gluon,  $u_v$ ,  $d_v$ ,  $\bar{U} = \bar{u} + \bar{c}$ ,  $\bar{D} = \bar{d} + \bar{s} + \bar{b}$   
 sea flavour break-up at  $Q_0$ :  $s=f_s\bar{D}$ ,  $c=f_c\bar{U}$ ,  $A(\bar{U})=(1-f_s)/(1-f_c)A(\bar{D})$ ; with  $f_s=0.33$ ,  $f_c=0.15$

(consistent with dynamical generation)

	A	B	C	D	E
gluon	sum rule				
$u_v$	sum rule				
$d_v$	sum rule	$B(u_v)$			
$\bar{U}$	$\lim_{x \rightarrow 0} \bar{u}/\bar{d} \rightarrow 1$				
$\bar{D}$		$B(\bar{U})$			

$$xg(x) = Ax^B(1-x)^C$$

$$xu_v(x) = Ax^B(1-x)^C(1+DX+Ex^2)$$

$$xd_v(x) = Ax^B(1-x)^C$$

$$x\bar{U}(x) = Ax^B(1-x)^C$$

$$x\bar{D}(x) = Ax^B(1-x)^C$$

parameter optimisation: start with **A,B,C** and add **D,E,F**... until no further  $X^2$  advantage

→ 11 free parameters

# HERA PDF parameterisation

## some more notes:

- HERA PDF parameterisation inspired by **both** H1 and ZEUS
  - but less model dependence on B parameters than H1
  - no need for additional  $x(\bar{u}-u)$  input, as in ZEUS
- H1 and ZEUS-style (**optimised**) parameterisations also looked at and used as **model cross-checks** (see backups)

## “HERA” PDF parameterisation:

- results in **best**  $X^2$  (although all three options are good)
- gives most **conservative** uncertainties

**HERA PDF parameterisation:** attempt at “best of both worlds”

# More details

## extra info on the fit:

- **NLO DGLAP framework** used to evolve PDFs in  $Q^2$
- **heavy flavour scheme: Zero-Mass Variable-Flavour-Number**  
[for now; but work ongoing with General-Mass VFN schemes]
- renormalisation and factorisation scales:  $Q^2$
- fit **573\* combined HERA-I NC and CC data** points
- total of **11 free parameters** in the PDF fit (details on previous slide)

## further fixed parameters:

- $Q_0^2 = 4 \text{ GeV}^2$  (**starting scale**)
- $Q_{\min}^2 = 3.5 \text{ GeV}^2$  (**minimum  $Q^2$  cut on fitted data**)
- $m_c = 1.4 \text{ GeV}$  (**charm mass**);  $m_b = 4.75 \text{ GeV}$  (**beauty mass**)
- $\alpha_s(M_Z) = 0.1176$  [PDG2006 value] (**strong coupling**)

\* from recent combination version where **only points with  $y < 0.35$  are transformed in  $E_p$**

# Systematic error treatment

HERA **combination** procedure has already taken **full account** of **correlated systematic uncertainties** in the data:-

choice of treatment of uncertainties in HERA PDF fit:-

- combine **43 systematic uncertainties** of the **data** with their statistical uncertainties, in **quadrature**;
- **OFFSET** the **4 systematic uncertainties** arising from the **combination**

$$X^2/\text{dof}=477/(573-11)$$

[also **checked**:- treat all 47 systematics:

- in quadrature:  **$X^2=428/562$**
- as correlated:  **$X^2=553/562$**

all three methods **give similar** PDF central values and uncertainties]

**self-consistency** and **small systematics** of the **combined HERA data** allows the use of  **$\Delta X^2=1$**  to calculate the PDF parameter uncertainties



# Model uncertainties

- several sources of model uncertainty considered:

(i) variations to be added to **total PDF uncertainty** (in quadrature):

	<b>model variation</b>	<b>nominal</b>	<b>variations</b>
$m_c$	charm mass (GeV)	1.4	<b>1.35, 1.5</b>
$m_b$	beauty mass (GeV)	4.75	<b>4.3, 5.0</b>
$f_s$	strange sea fraction at $Q_0^2$	0.33	<b>0.25, 0.40</b>
$f_c$	charm sea fraction at $Q_0^2$	0.15	<b>0.12, 0.18</b>
$Q_0^2$	starting scale (GeV <sup>2</sup> )	4.0	<b>2.0, 6.0</b>
$Q_{\min}^2$	cut on data included (GeV <sup>2</sup> )	3.5	<b>2.5, 5.0</b>

[ NB. **correlated variations**: i. for  $Q_0^2$  variation,  $f_s$  and  $f_c$  also varied;  
ii. for  $m_c$  variation,  $f_c$  also varied ]

(ii) variations used as **model cross-checks** (shown in backups):

	<b>model variation</b>	<b>nominal</b>	<b>variations</b>
$\alpha_s(M_Z)$	strong coupling	0.1176	<b>0.1156, 0.1196</b>
$xf(x)$	PDF parameterisation	“HERA”	<b>H1-, ZEUS-styles</b>

# Results (i): NC e<sup>+</sup>p comparison

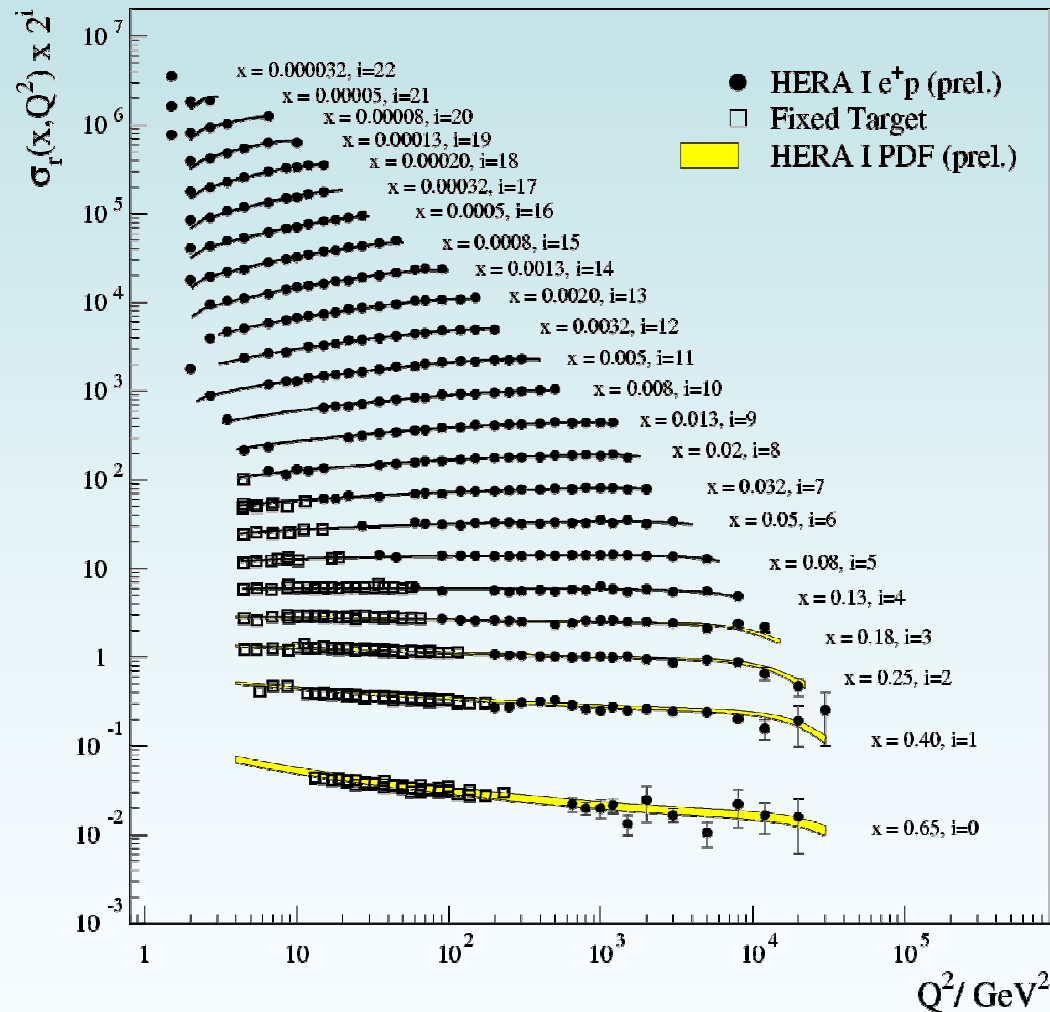
Neutral Current e<sup>+</sup>p

“**HERAPDF0.1**”:  
fit quality to the  
combined HERA-I  
data for **NC e<sup>+</sup>p**

uncertainties on both  
data and fit included

beautifully **precise** data:-  
very well described by  
**HERA-I PDF** [uncertainties  
can barely be resolved  
except at highest x, Q<sup>2</sup>]

H1 and ZEUS Combined PDF Fit



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# Results (ii): NC e<sup>+</sup>p comparison

Neutral Current e<sup>+</sup>p

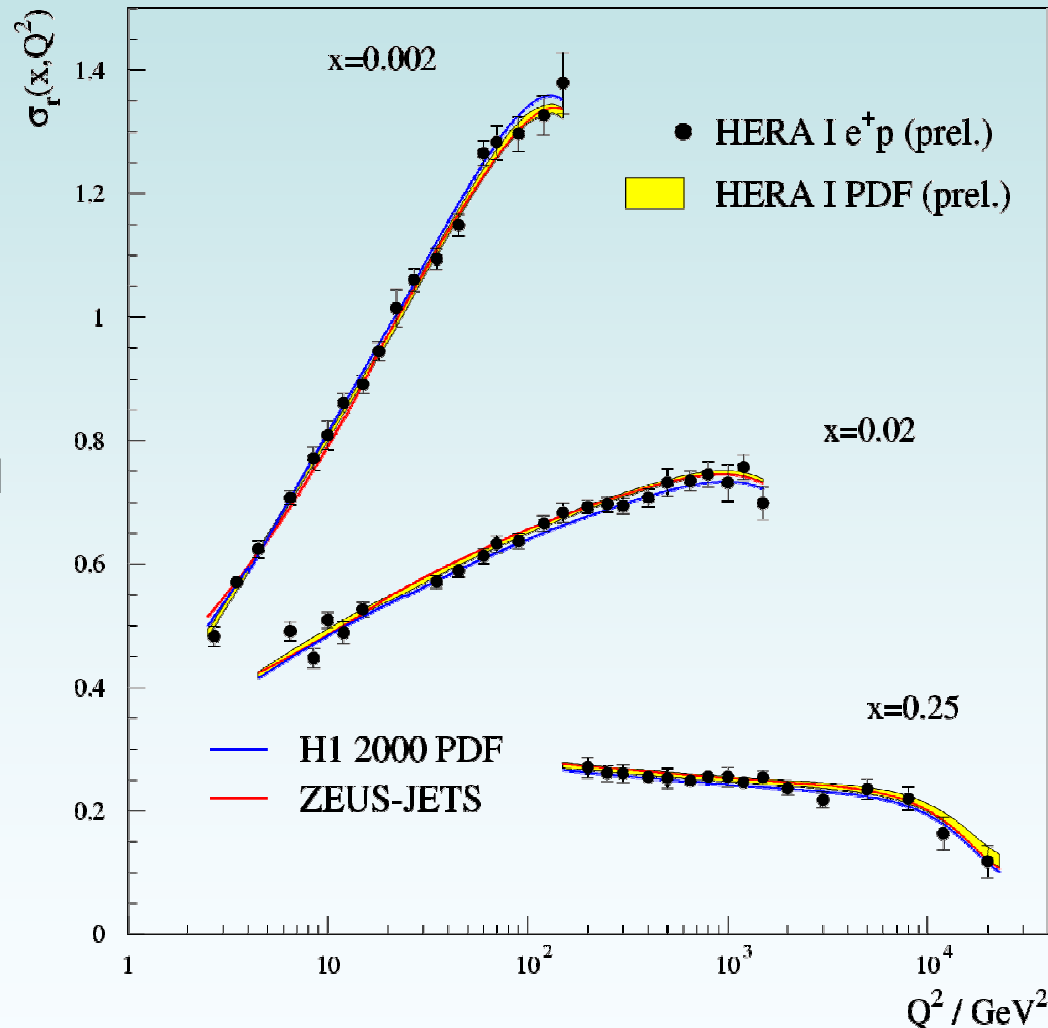
**in more detail:**

zoom in on **three x-values** from plot on previous slide

**“HERAPDF0.1”** is compared to previously published PDFs from **H1** and **ZEUS**

scaling violations at low x clearly visible → **tight constraints on gluon**

H1 and ZEUS Combined PDF Fit



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# Results (iii): NC $e^\pm p$

NC  $e^\pm p$  [at high  $Q^2$ ]

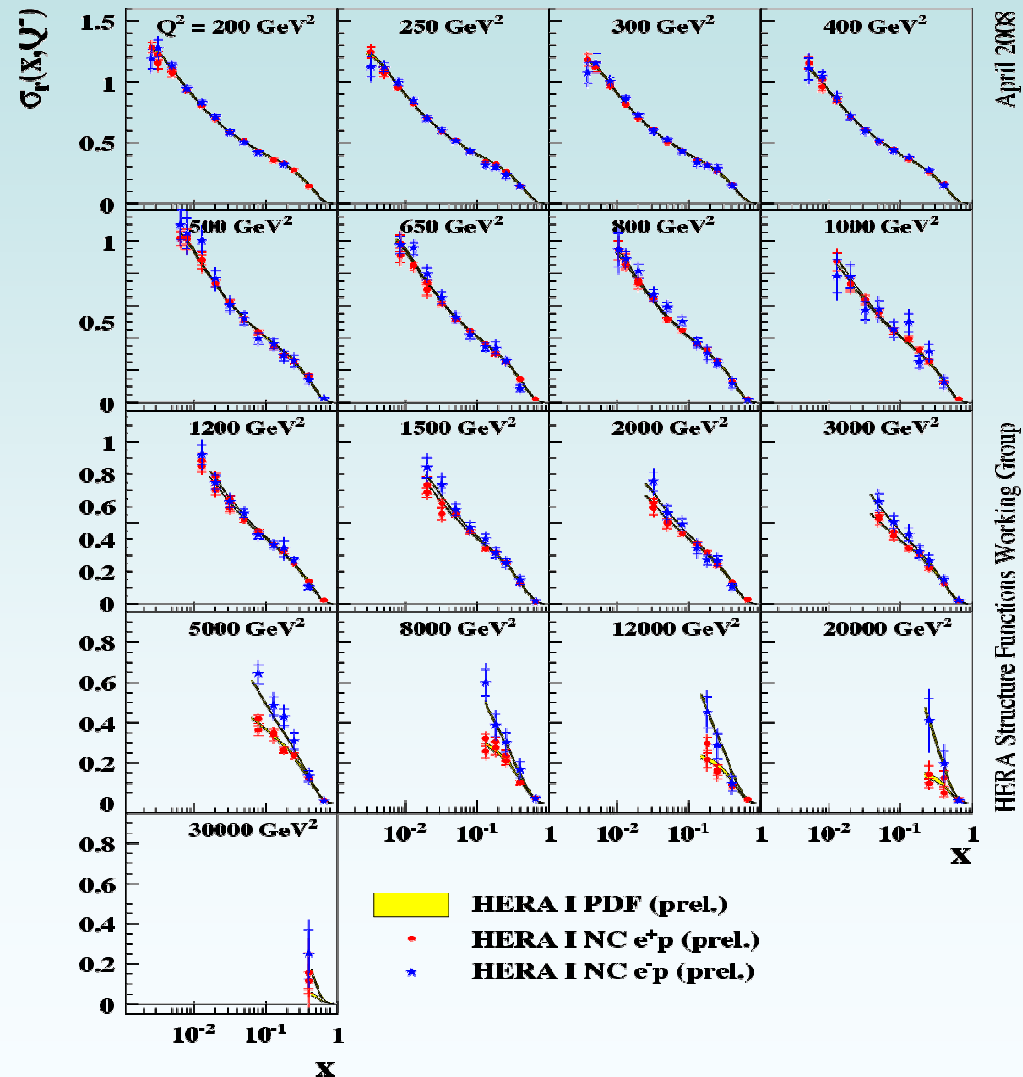
“HERAPDF0.1”:

fit quality to the  
combined HERA-I  
data for NC  $e^+p$  and  
 $e^-p$  at high  $Q^2$

uncertainties on both  
data and fit included

difference between  $e^+p$   
and  $e^-p$  NC at high  $Q^2$  gives  
 $x F_3 \rightarrow$  direct sensitivity  
to valence quarks

H1 and ZEUS Combined PDF Fit



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# Results (iv): CC $e^\pm p$

Charged Current  $e^\pm p$

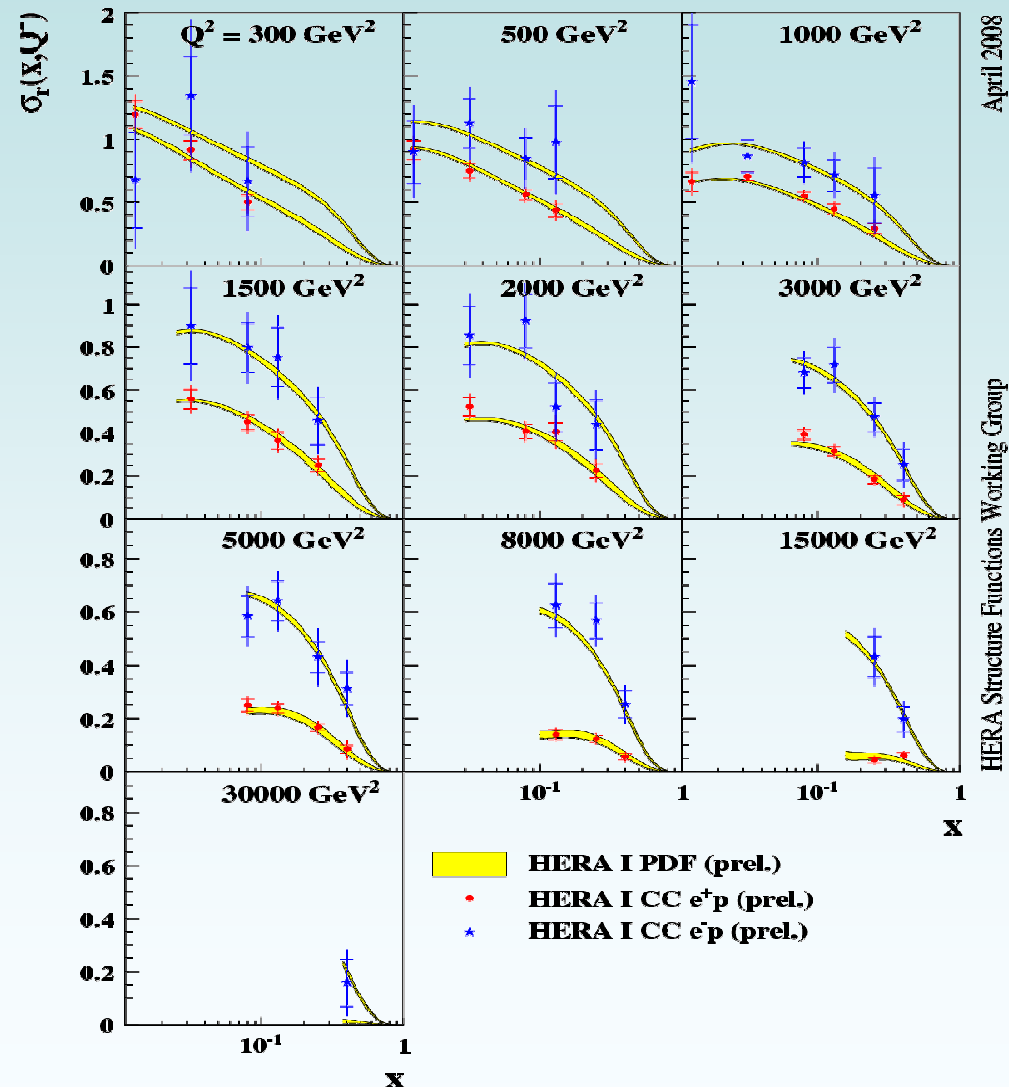
“**HERAPDF0.1**”:  
fit quality to the  
combined HERA-I  
data for **CC  $e^+p$  and  
 $e^-p$  at high  $Q^2$**

uncertainties on both  
data and fit included

difference between  $e^+p$  and  
 $e^-p$  CC **constrains flavour  
composition** of proton

[avoids **nuclear corrections**  
from fixed target data]

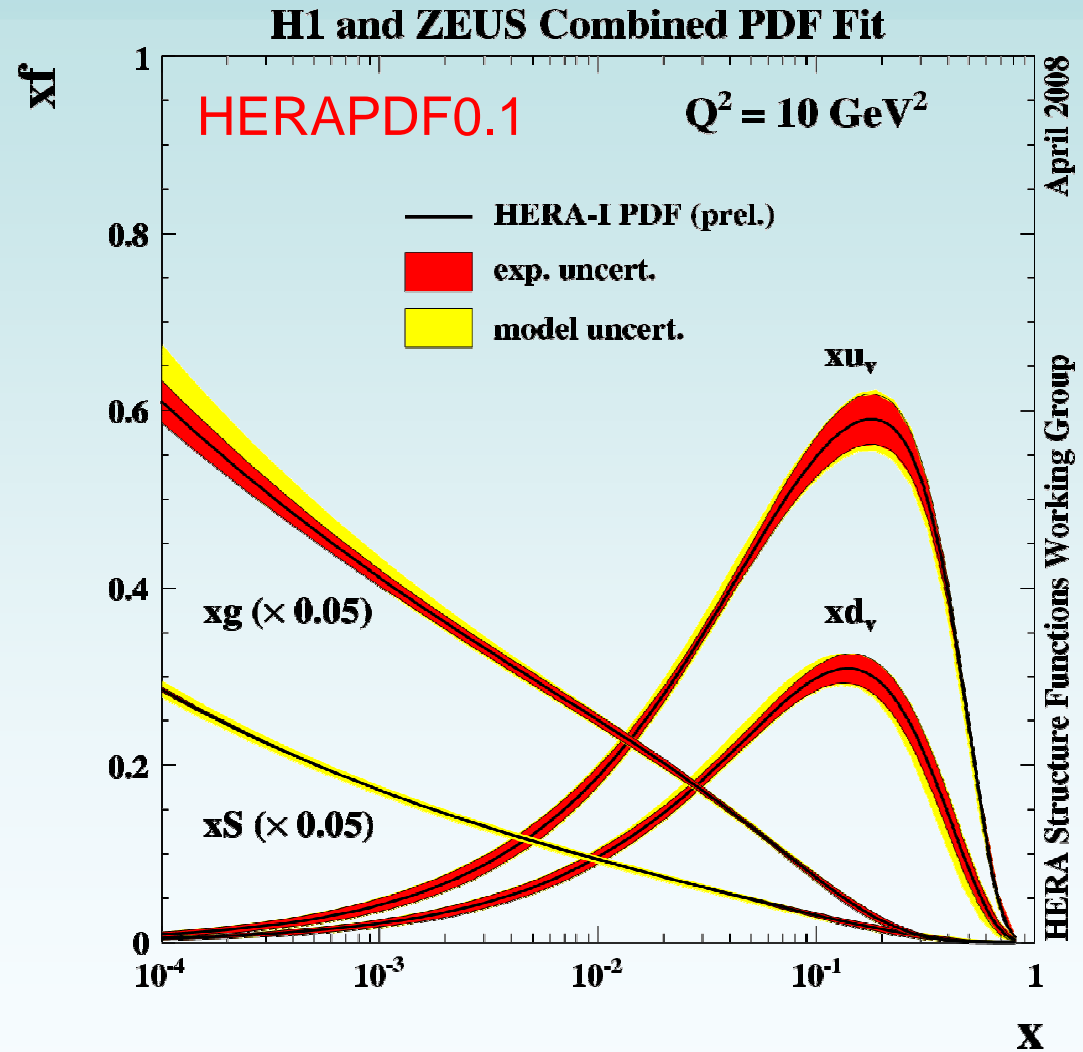
H1 and ZEUS Combined PDF Fit



# HERA PDF

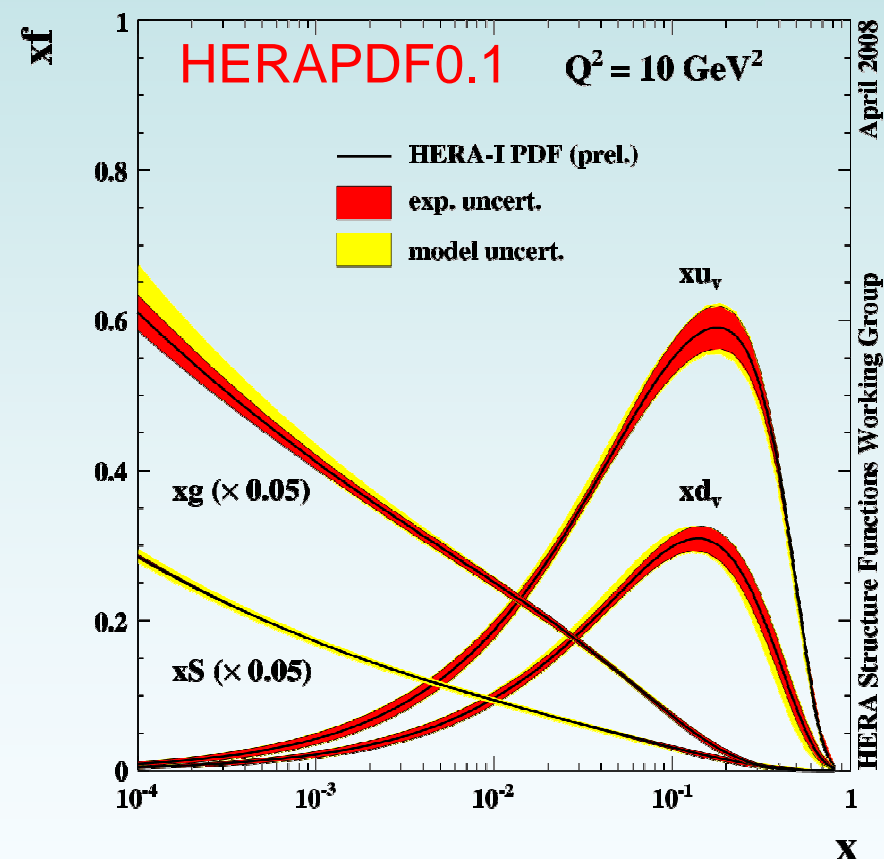
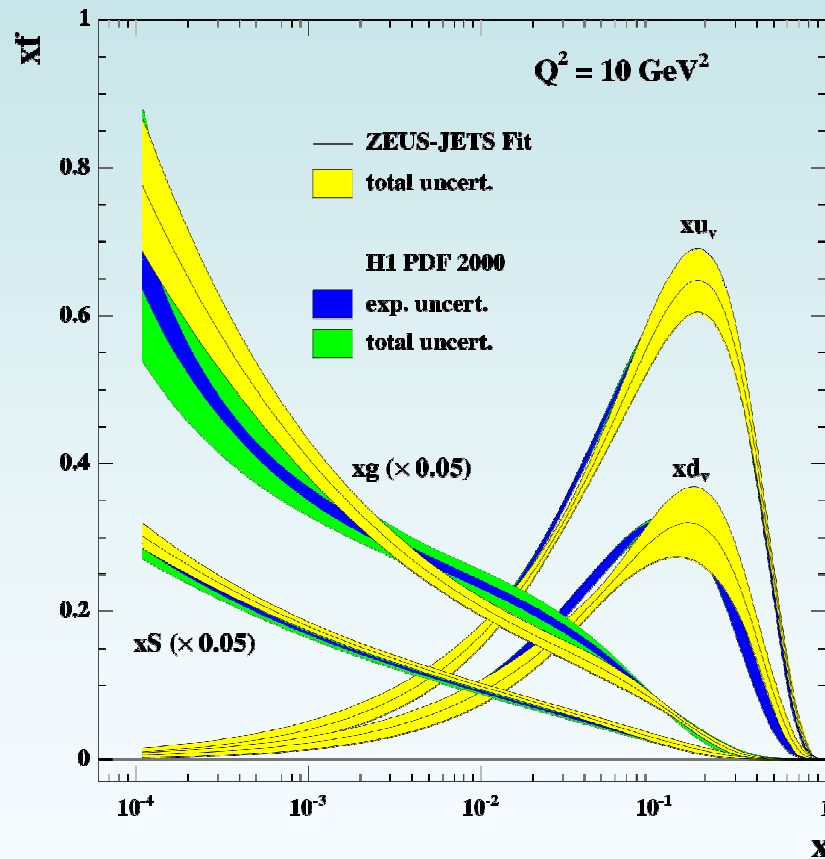
“HERAPDF0.1”:  
total **experimental**  
**uncertainty** band and  
**model uncertainties**

Note:  $xg(x)$  and  $xS(x)$   
scaled down by  $\times 20$



# cf. previous fits to HERA data

Comparison with H1 and ZEUS published fits to their own HERA-I data



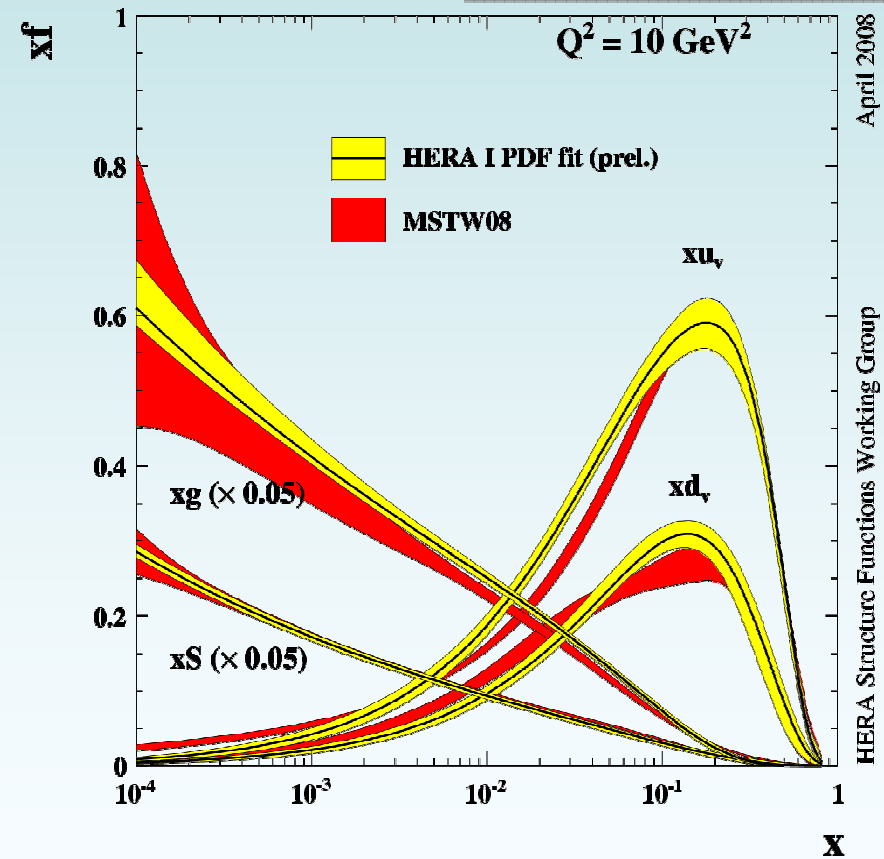
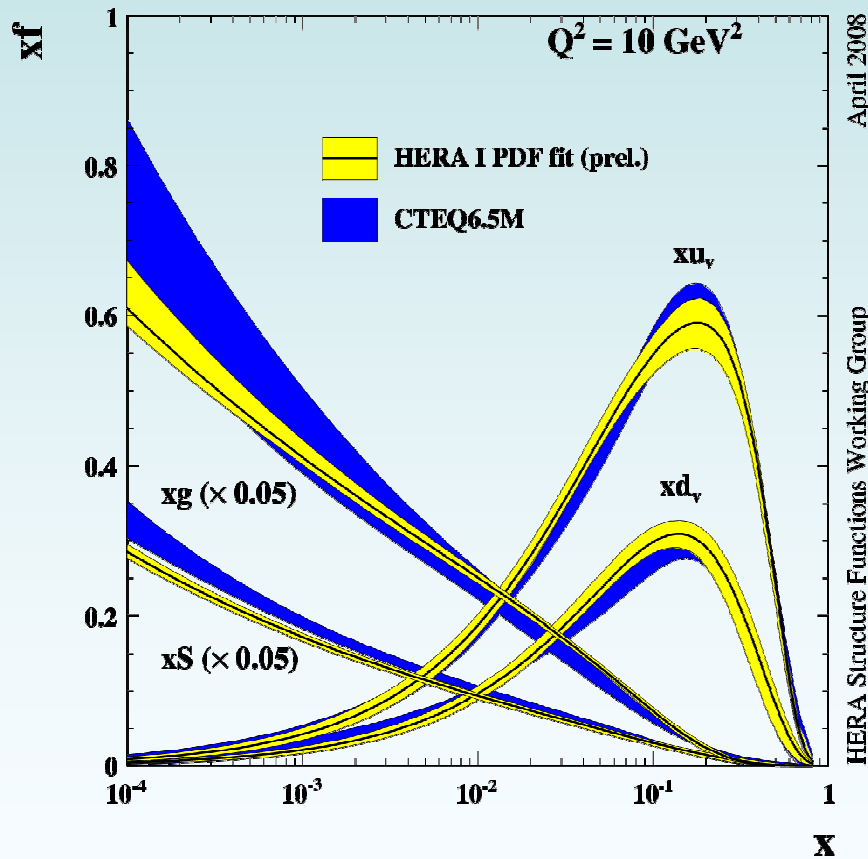
improvement in precision is impressive: originates from data combination

# HERA PDF vs. Global fits

Comparison with recent **CTEQ** and **MSTW** PDFs

## Caution:

- Different  $\Delta X^{2'}$ s ... also:
- global fits: 90% CL
  - HERA fit: 68% CL



[ note that **MSTW08** is not yet published:- this is a **pre-release** ]

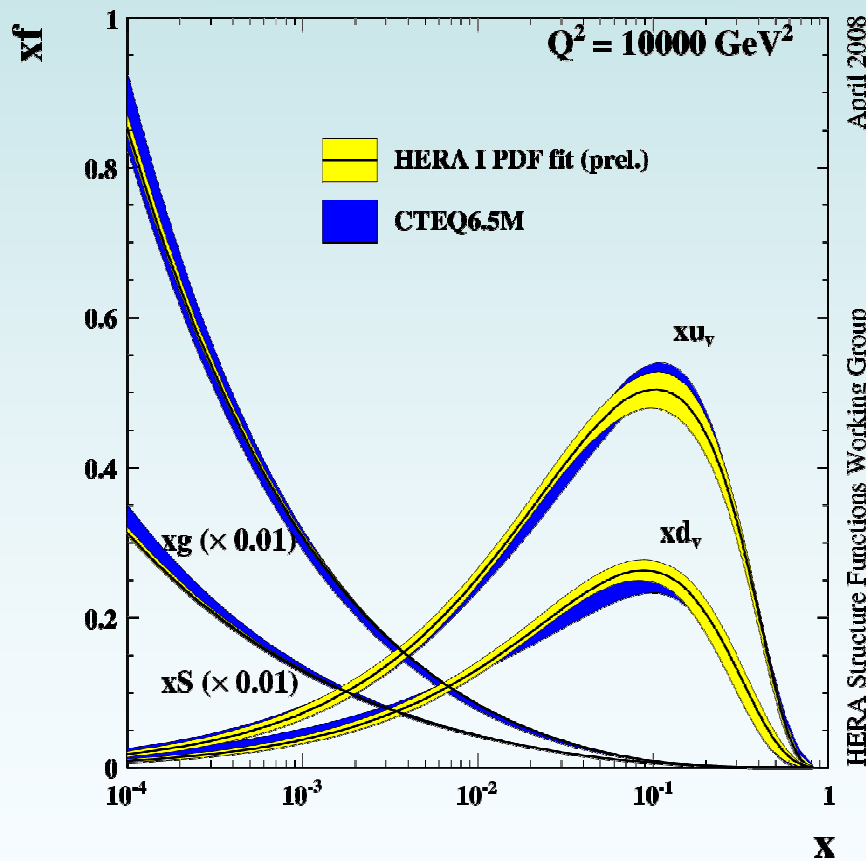


# HERA PDF vs. Global fits

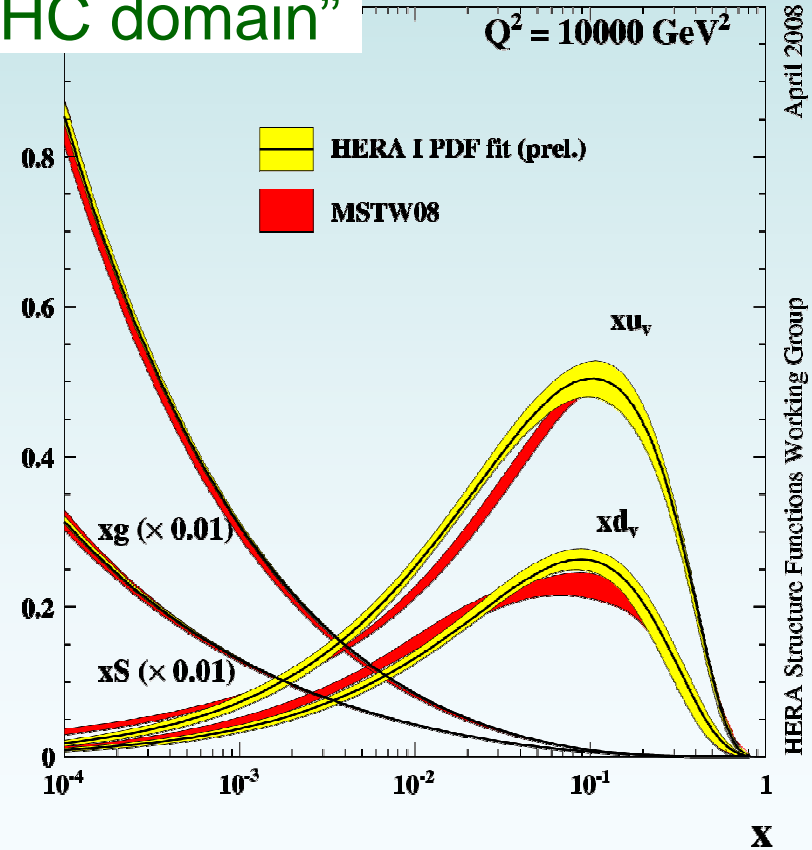
Comparison with recent **CTEQ** and **MSTW** PDFs

## Caution:

- Different  $\Delta X^2$ 's ... also:
- global fits: 90% CL
  - HERA fit: 68% CL



“LHC domain”

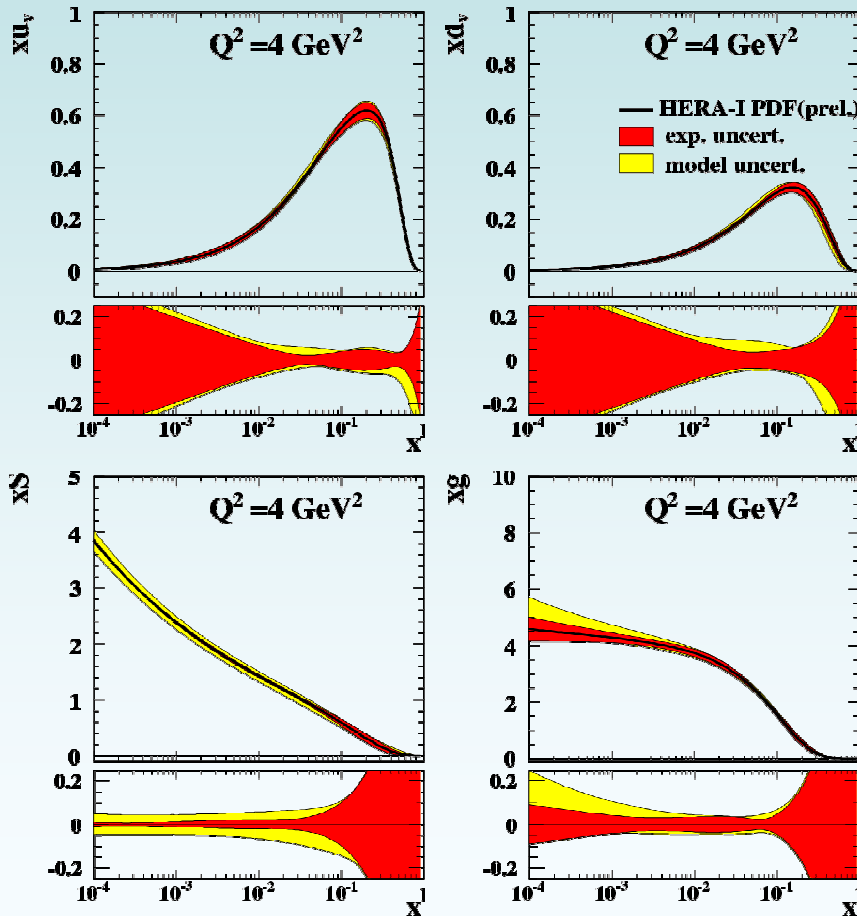


[ note that **MSTW08** is not yet published:- this is a **pre-release** ]

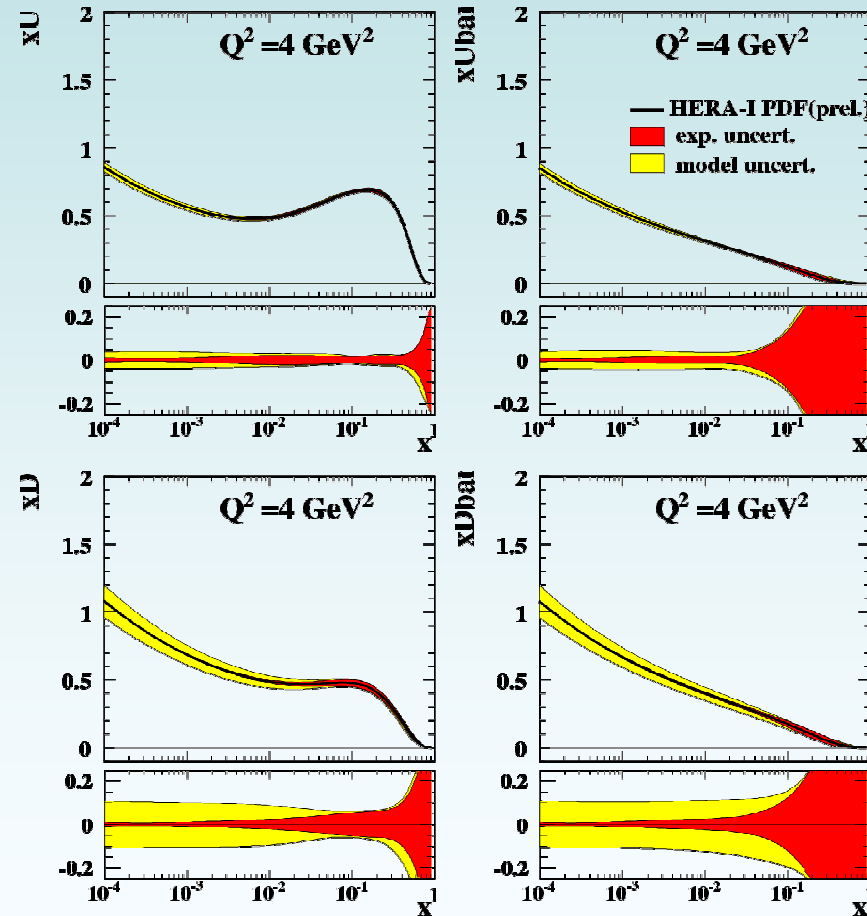
# HERA PDF: in more detail

PDFs at starting scale,  $Q_0^2=4 \text{ GeV}^2$

H1 and ZEUS Combined PDF Fit



H1 and ZEUS Combined PDF Fit



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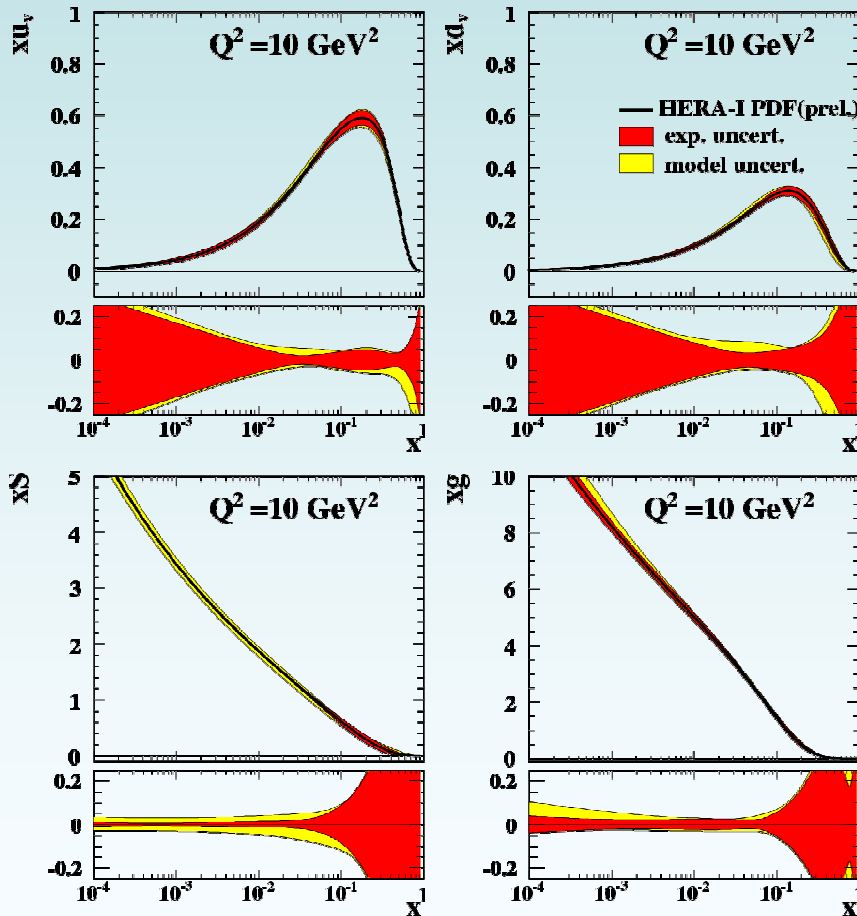
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$f_s$  dominates model uncertainty on sea;  $Q_0^2$  and  $Q_{min}^2$  dominate  $xg$  and  $xq_v$

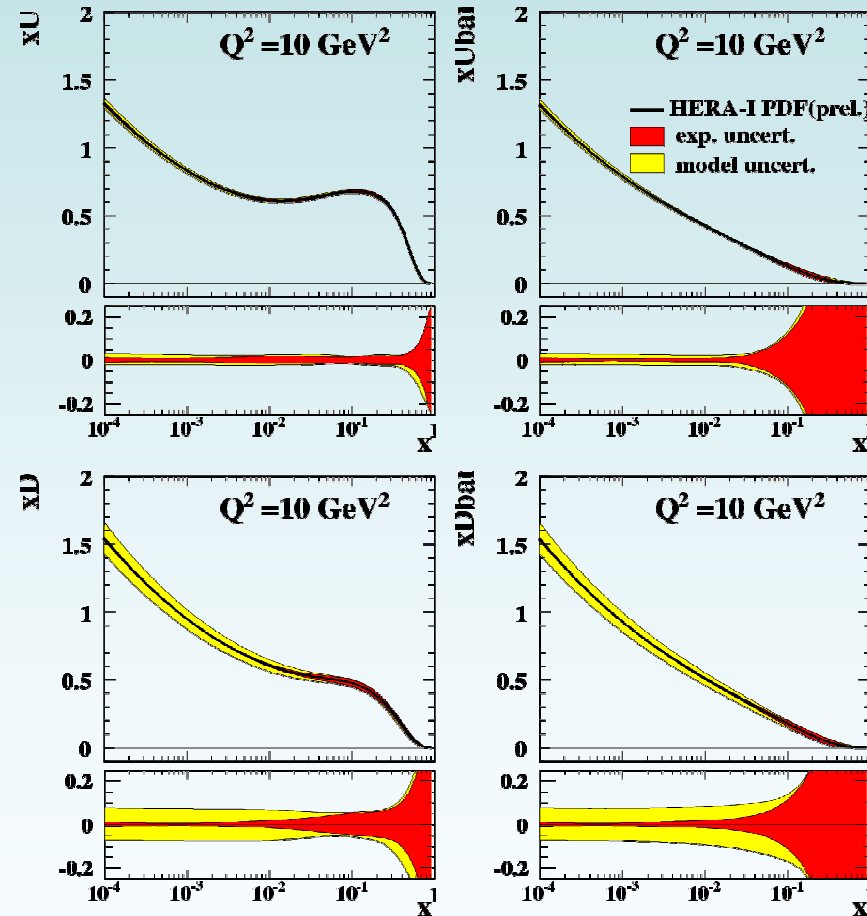
# HERA PDF: in more detail

PDFs at  $Q^2=10 \text{ GeV}^2$

H1 and ZEUS Combined PDF Fit



H1 and ZEUS Combined PDF Fit



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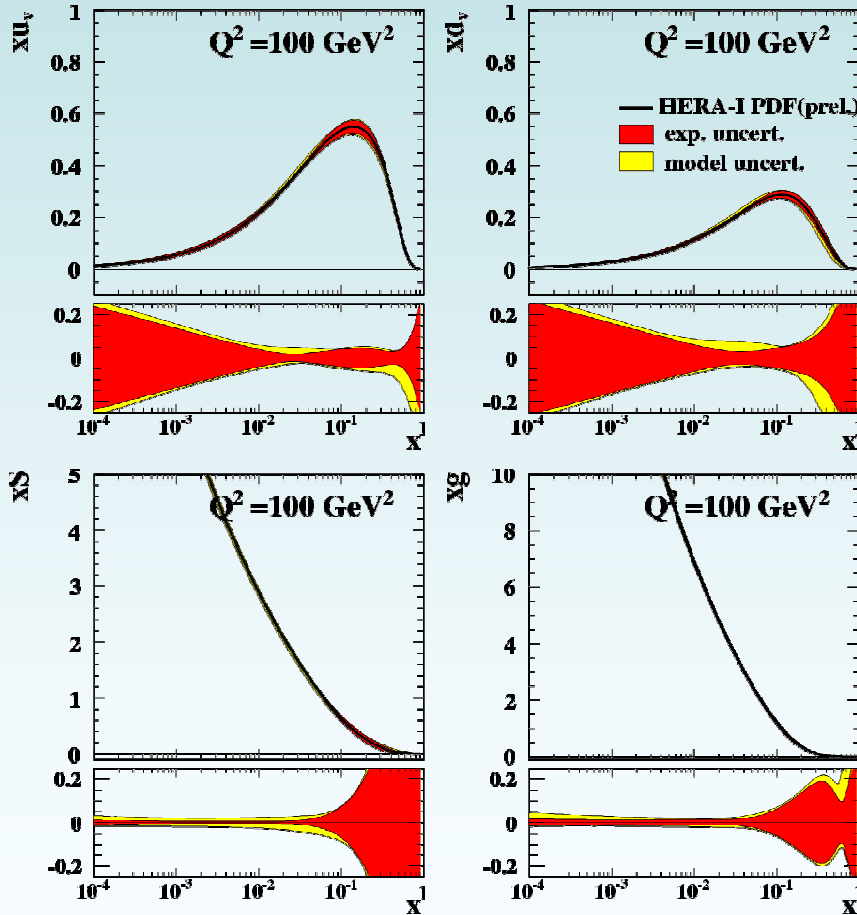
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PDF uncertainties decrease as  $Q^2$  increases

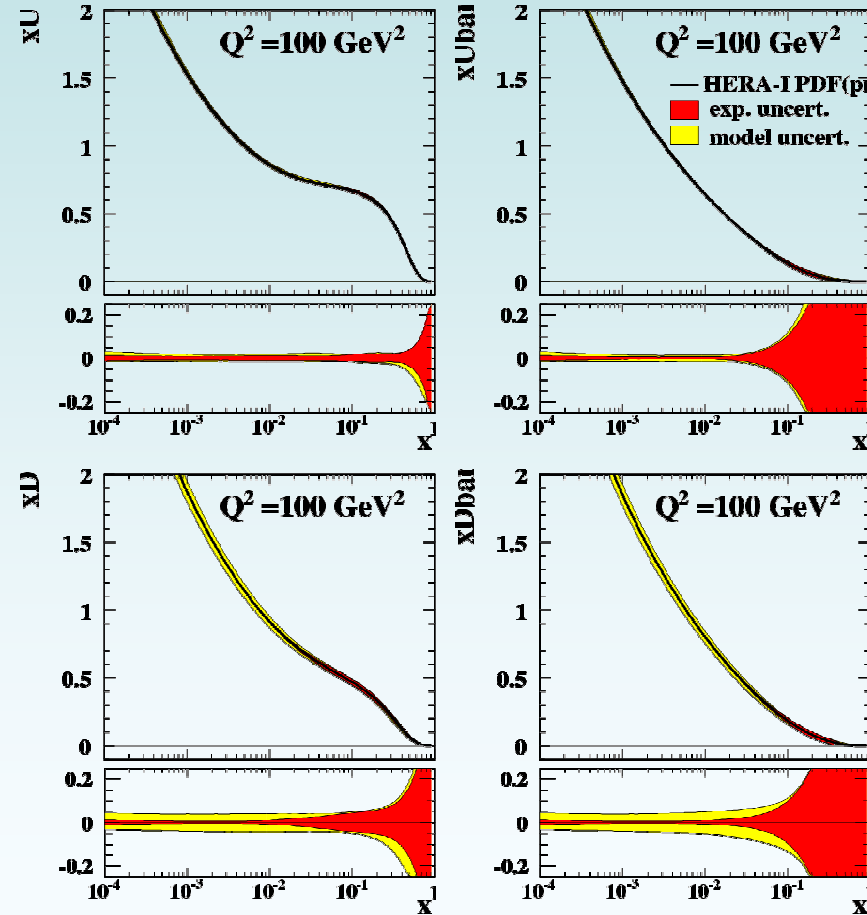
# HERA PDF: in more detail

PDFs at  $Q^2=100 \text{ GeV}^2$

H1 and ZEUS Combined PDF Fit



H1 and ZEUS Combined PDF Fit



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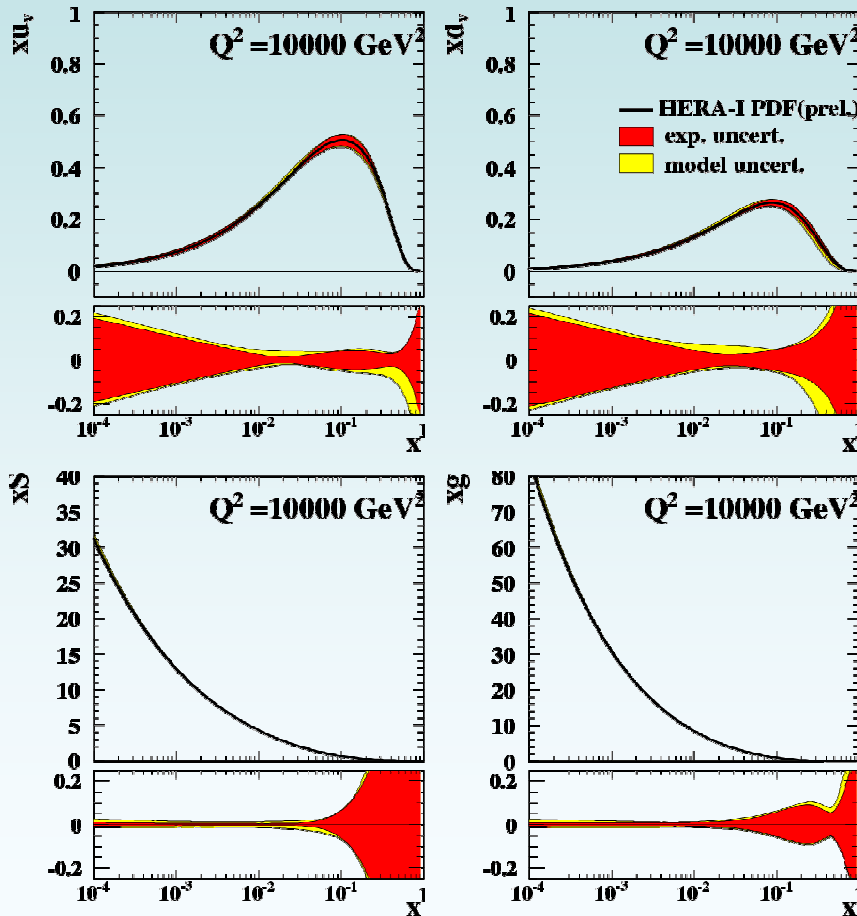
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PDF uncertainties decrease as  $Q^2$  increases

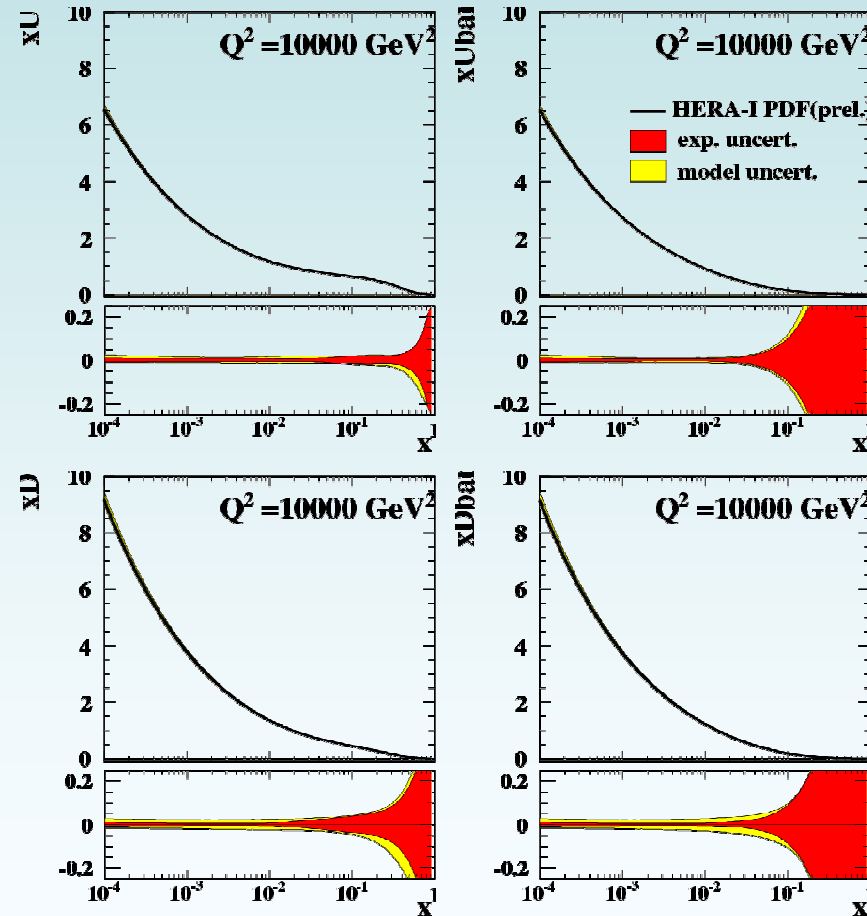
# HERA PDF: in more detail

PDFs at  $Q^2=10000 \text{ GeV}^2$

H1 and ZEUS Combined PDF Fit



H1 and ZEUS Combined PDF Fit



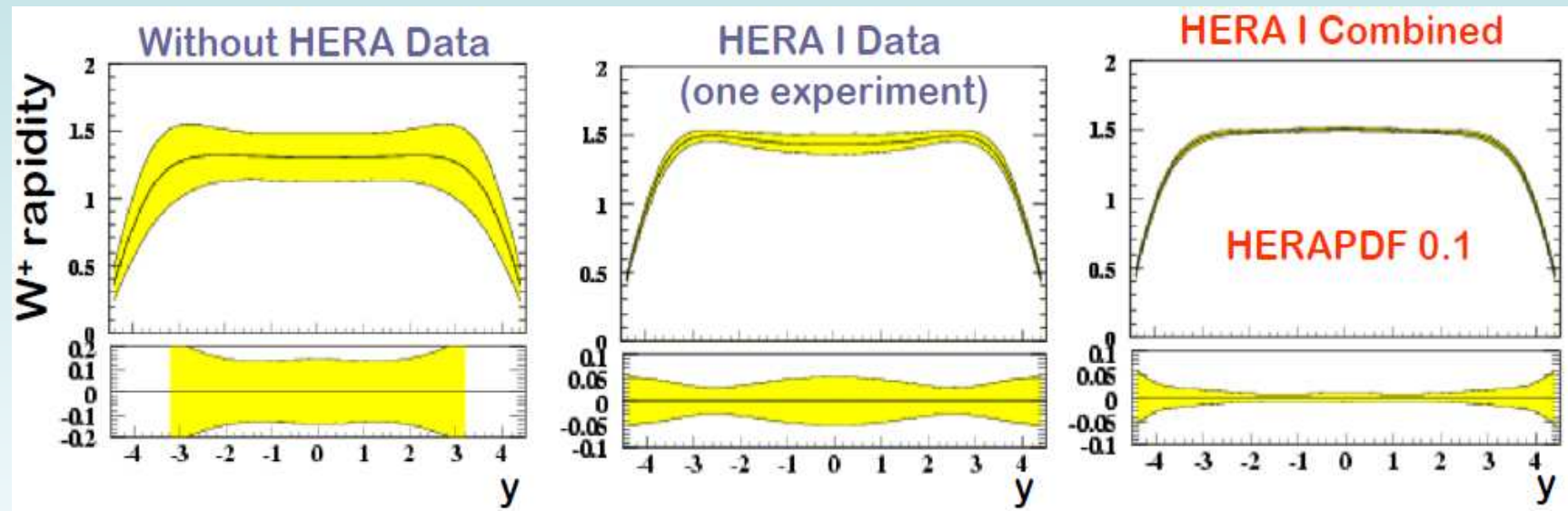
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scale relevant for LHC:- impressively small uncertainties

# HERA PDF: impact

**EXAMPLE:**  $W^+$  production at the LHC (study by A. Cooper-Sarkar)



- **HERA combined data** and **PDFs** will be crucial input for LHC predictions  
note, in these plots, uncertainty bands are from experimental sources only  
→ step in **experimental precision** is striking  
→ model uncertainties will become increasingly important ...

[see also: A. Cooper-Sarkar and E. Perez - talk at the HERA-LHC ws, May'08]

# LHAPDF?

**HERAPDF0.1** very soon to be **released** in **LHAPDFv5.6.0**

will be available in both following forms:

- input parameters + evolution code (“.LHpdf”-style)
- PDF values on  $(x, Q^2)$  grid (“.Lhgrid”-style)

## Note for users:

- to obtain experimental uncertainties, sum over  $N_{\text{mem}}=1-22$
- to obtain experimental+model uncertainties, sum over  $N_{\text{mem}}=1-34$   
[for technical reasons, model uncerts. only available in “.Lhgrid”-style]

# Summary

- **HERA** combination of inclusive NC and CC DIS data
  - robust, model-independent combination procedure developed
    - H1 and ZEUS experiments **cross-calibrate** each other
    - significantly **improved** systematics as well as statistics
  - hope to **publish** combined data within a few months  
[H1 has a couple of HERA I NC datasets still to be published]
- HERA **PDF fit** to combined data
  - NLO QCD fit to combined HERA-I data
    - uses ep data only → no need for nuclear corrections
    - results in a HERA PDF with **impressive precision** compared to previous HERA analyses and to global fits
  - very soon to be released in LHAPDF

still to come:- use of all **HERA-II** data in both combination and fits



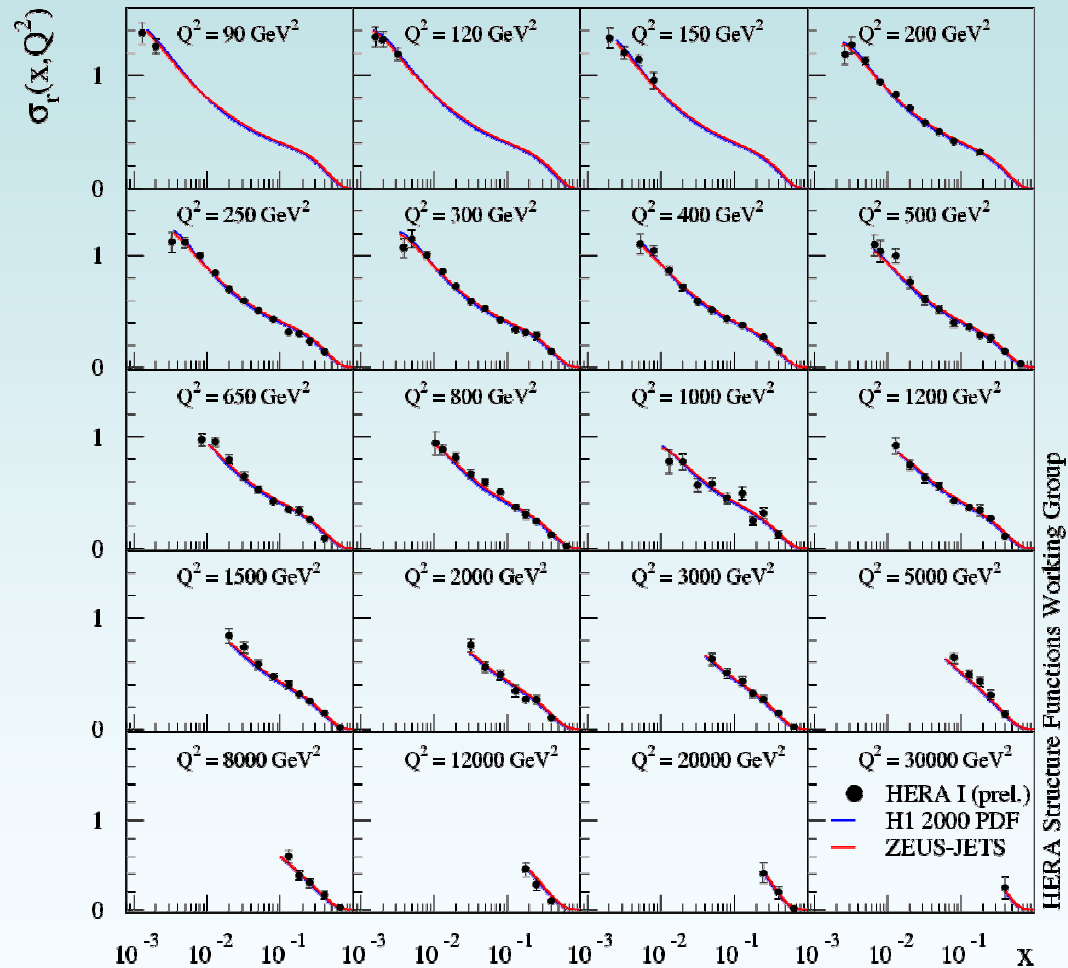
# Extras

---

# Results (extra): NC e-p

NC e-p [at high  $Q^2$ ]:  
combined data compared  
to published **H1** and **ZEUS**  
PDF fits to (their own)  
data from HERA I

HERA I e-p Neutral Current Scattering - H1 and ZEUS

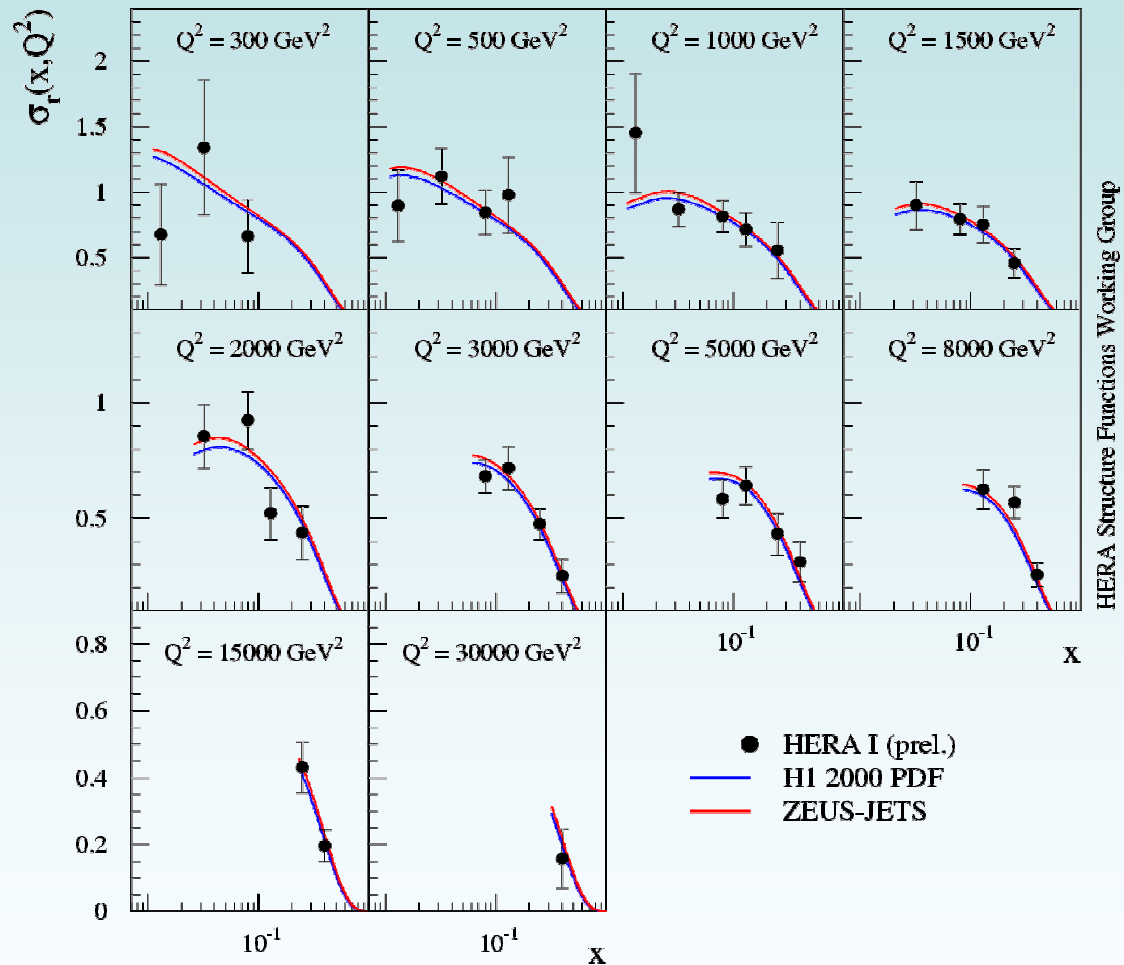


# Results (extra): CC e-p

## CC e-p:

combined data compared to published **H1** and **ZEUS** PDF fits to (their own) data from HERA I

HERA I e-p Charged Current Scattering - H1 and ZEUS



# Alternative parameterisations (i)

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

“H1-style”-parameterisation [as used in H1PDF2k]:

partons parameterised: gluon,  $U=u+c$ ,  $D=d+s+b$ ,  $\bar{U} = \bar{u}+c$ ,  $\bar{D} = \bar{d}+s+b$   
 sea flavour break-up at  $Q_0$ :  $s=f_s\bar{D}$ ,  $c=f_c\bar{U}$ ,  $A(\bar{U})=(1-f_s)/(1-f_c)A(\bar{D})$ ; with  $f_s=0.33$ ,  $f_c=0.15$

	A	B	C	D	E	F
gluon	sum rule					
U	$\lim_{x \rightarrow 0} \bar{u}/\bar{d} > 1$			sum rule		
D		=B(U)		sum rule		
$\bar{U}$	=A(U)	=B(U)				
$\bar{D}$	=A(D)	=B(U)				

# Alternative parameterisations (ii)

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

“ZEUS-style”-parameterisation [as used in ZEUS-Jets]:

partons parameterised: gluon,  $u_v$ ,  $d_v$ , sea =  $u_{\text{sea}} + \bar{u} + d_{\text{sea}} + \bar{d} + s + \bar{s} + c + \bar{c}$   
 sea flavour break-up at  $Q_0$ :  $s = (\bar{u} + \bar{d})/4$ , charm dynamically generated,  $\bar{d} - \bar{u}$  fixed to E866 data

	A	B	C	D	E
gluon	sum rule				0.
$u_v$	sum rule				
$d_v$	sum rule	=B( $u_v$ )			0.
sea				0.	0.
$\bar{u} - \bar{d}$	parameters from ZEUS-S global fit (2002)			0.	0.

# Offset method

**HERA PDF fit: 4 correlated procedural uncertainties**, arising from the data combination method, are treated with the **Offset method**

## Offset Method (in a nutshell)

1. perform fit without correlated uncertainties for central fit
2. shift measurements to upper limit of one of its systematic uncertainties
3. redo fit, record differences of parameters from those of step 1
4. go back to 2, shift measurement to lower limit
5. go back to 2, repeat 2-4 for next source of systematic (and so on ...)
6. add all deviations from central fit in quadrature (positive and negative deviations separately)

Does **not** assume uncertainties are **Gaussian distributed**. Also tends to give **more conservative uncertainty estimates** than other methods.

**Note:** clever ways to do this in practice [Pascaud and Zomer LAL-95-05, Botje hep-ph-0110123] 53

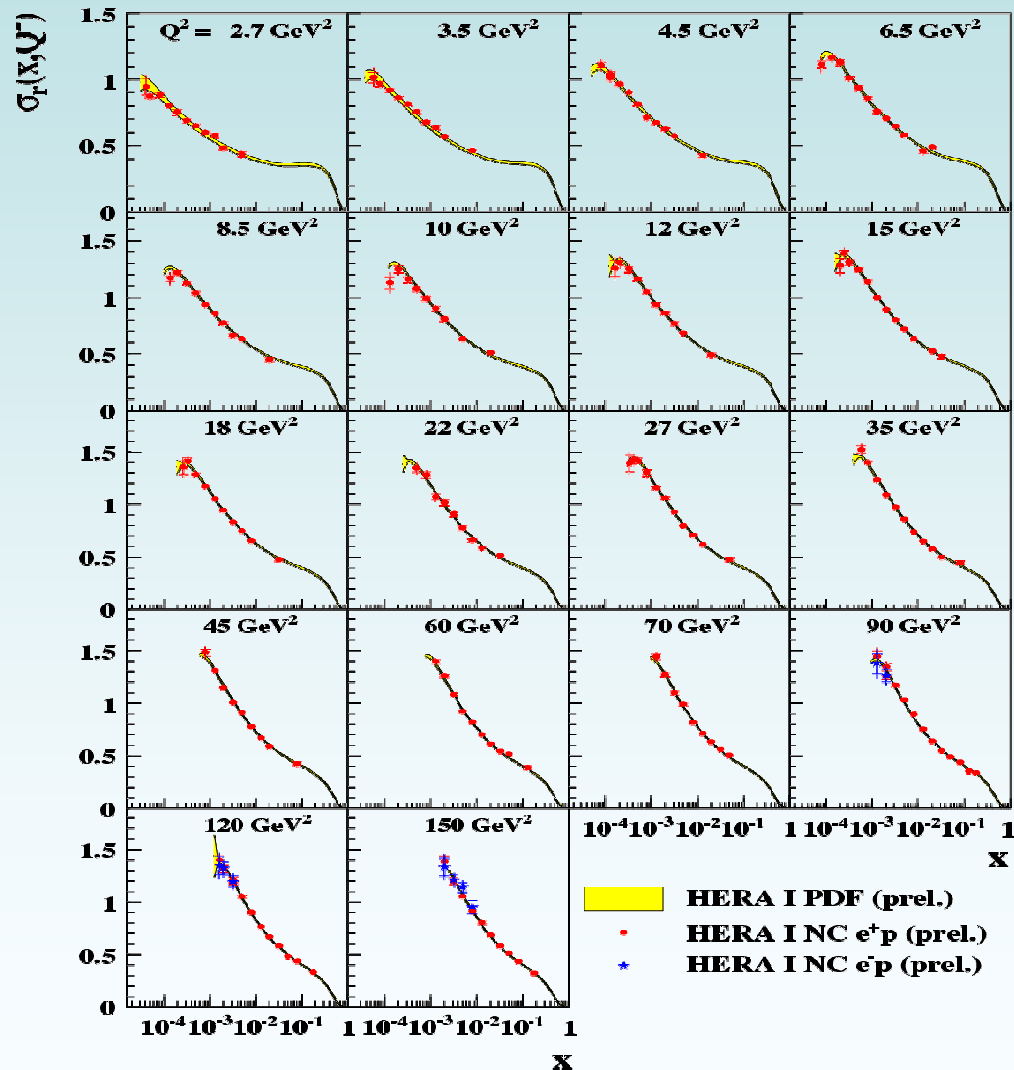
# Results (extra): NC $e^\pm p$

NC  $e^\pm p$  [at low  $Q^2$ ]

**“HERAPDF0.1”**:  
fit quality to the  
combined HERA-I  
data for **NC  $e^+p$**  and  
 **$e^-p$**  at high  $Q^2$

uncertainties on both  
data and fit included

H1 and ZEUS Combined PDF Fit



April 2008

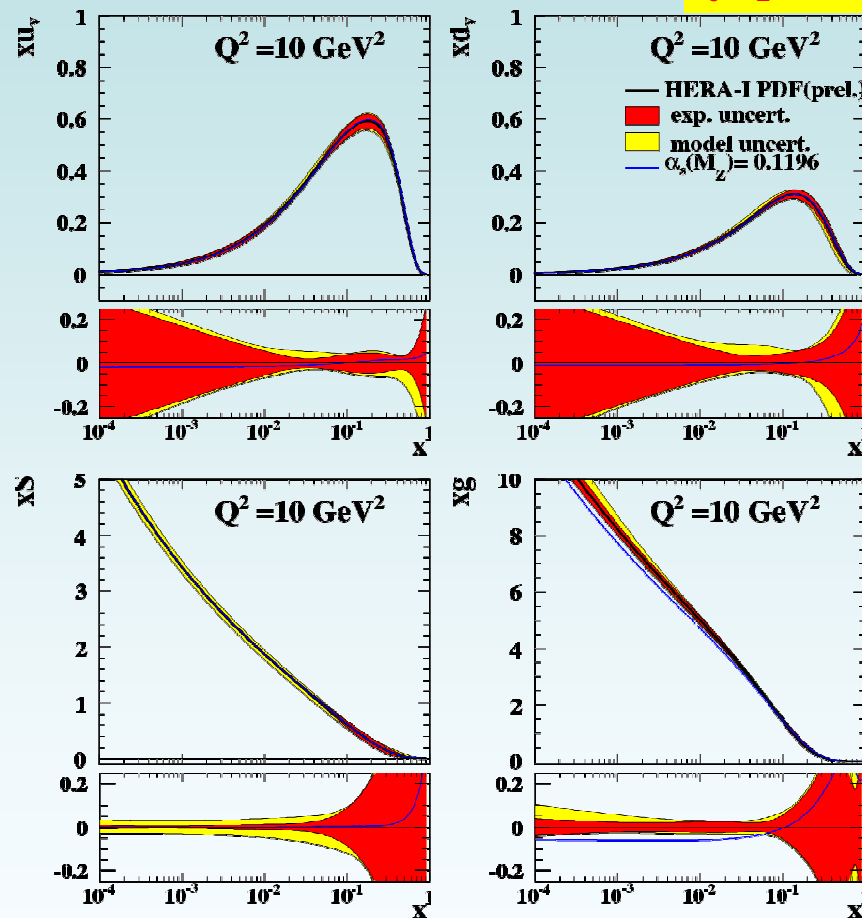
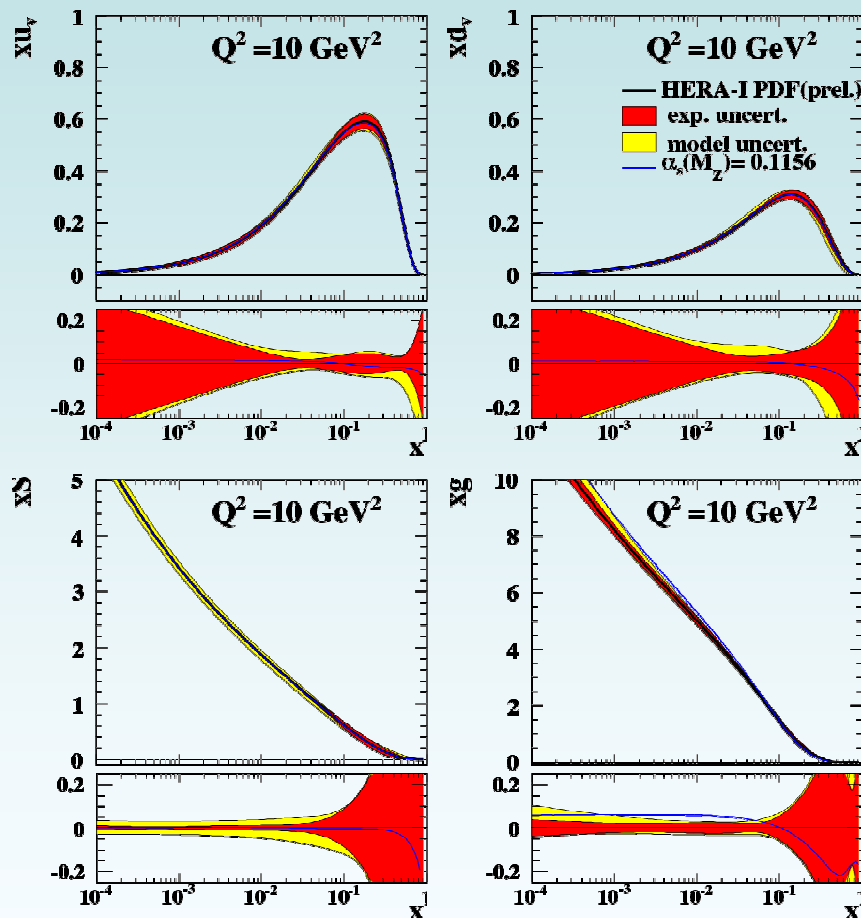
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# Model cross-checks

$\alpha_s$ -variation cf. nominal:  $\alpha_s(M_Z)=0.1176$

H1 and ZEUS Combined PDF Fit  $\alpha_s(M_Z)=0.1156$

H1 and ZEUS Combined PDF Fit  $\alpha_s(M_Z)=0.1196$



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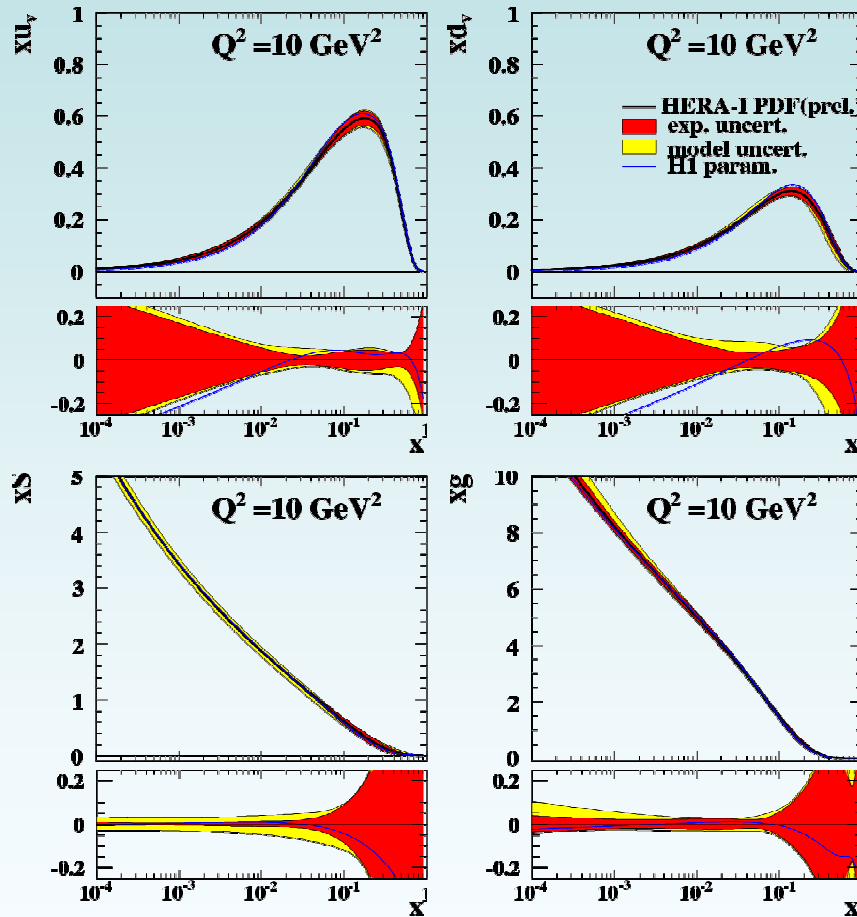
variations outside gluon uncertainty bands (even including model uncertainty)



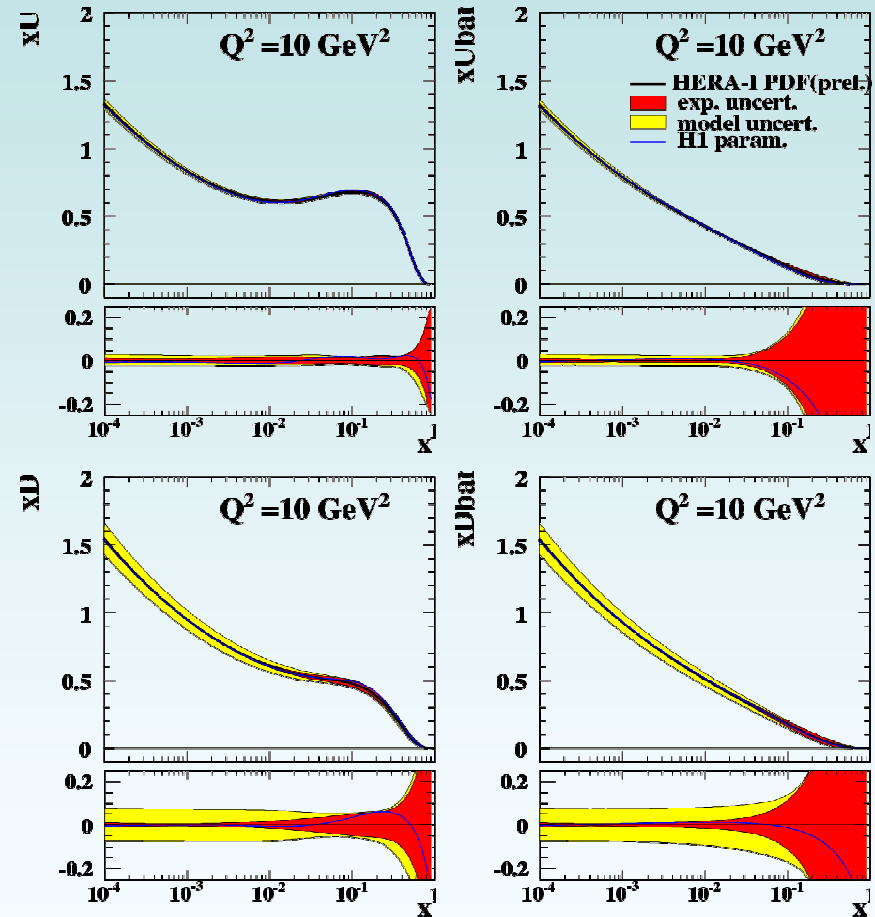
# Model cross-checks

## H1-style parameterisation

H1 and ZEUS Combined PDF Fit



H1 and ZEUS Combined PDF Fit



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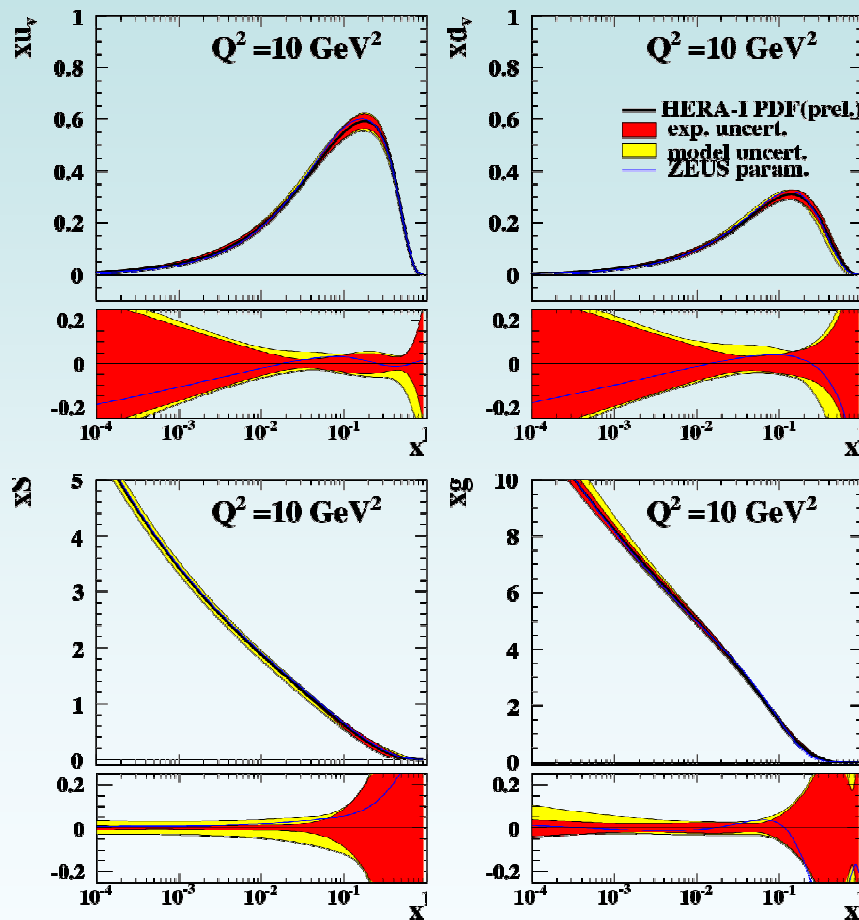
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HERA-I PDF compared to central value of H1-style param. (optimised)

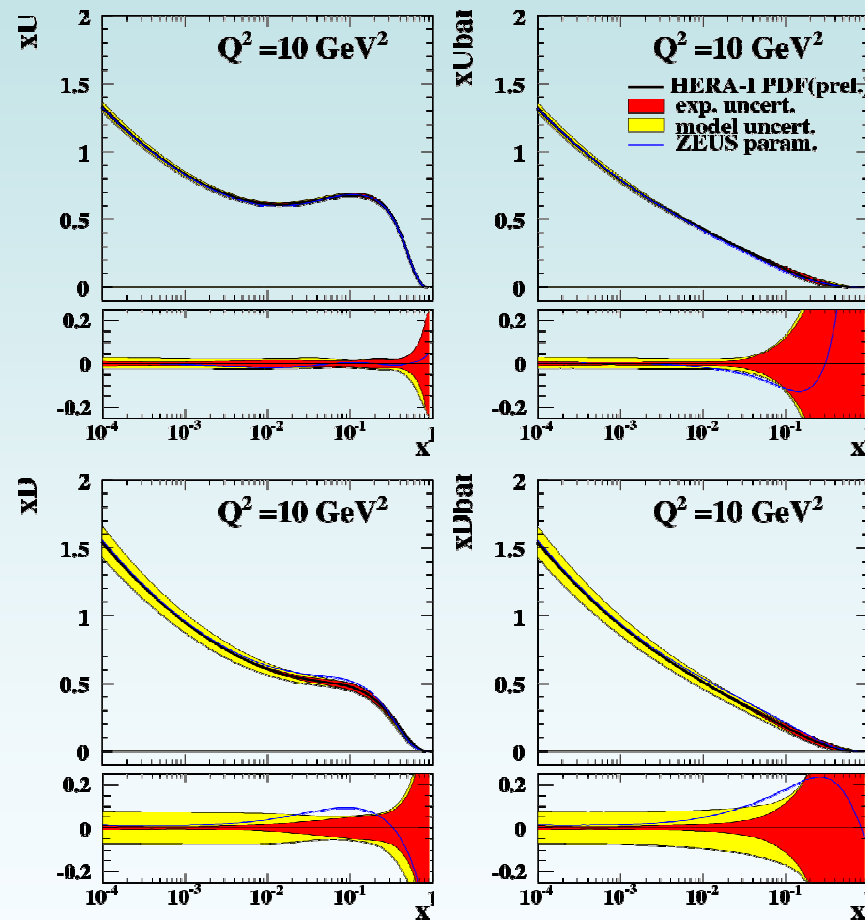
# Model cross-checks

ZEUS-style parameterisation

H1 and ZEUS Combined PDF Fit



H1 and ZEUS Combined PDF Fit



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HERA-I PDF compared to central value of ZEUS-style param. (optimised)

# “straight” vs. “humpy” gluon

Resolution of an old discrepancy:

**issue:** H1 fits always produced a “humpy” shaped gluon, ZEUS did not

**explanation:** if a non-zero D-parameter used for the gluon, **two minima** are found (for any of the parameterisations):

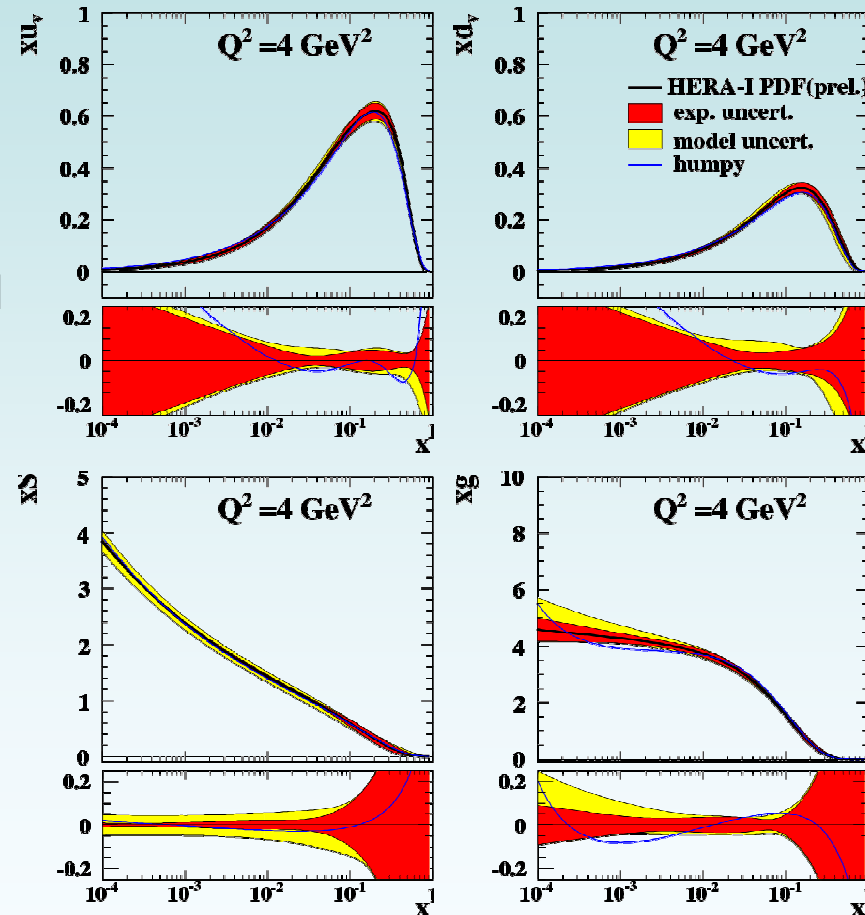
“**straight**” and “**humpy**” solutions

**HERA combined data set:-**

“**straight**” gluon solution favoured by about 10  $X^2$  points [but “humpy” gluon still acceptable!]

Opposite: “**straight**” and “**humpy**” solutions are compared  $\rightarrow$  results are very **consistent**

H1 and ZEUS Combined PDF Fit



April 2008

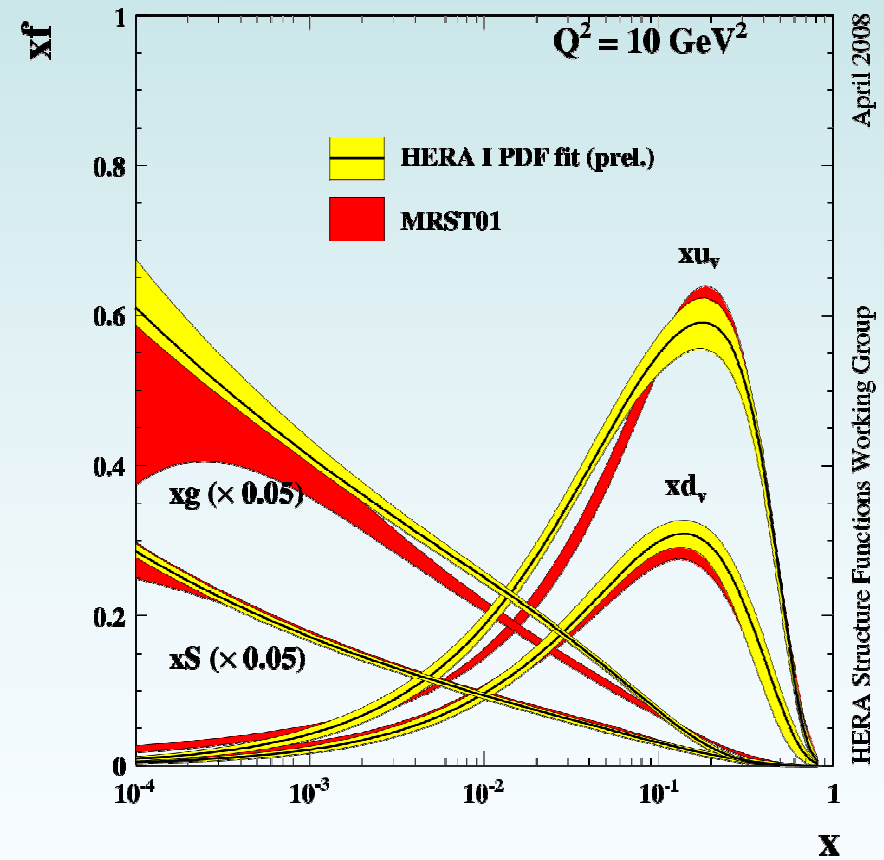
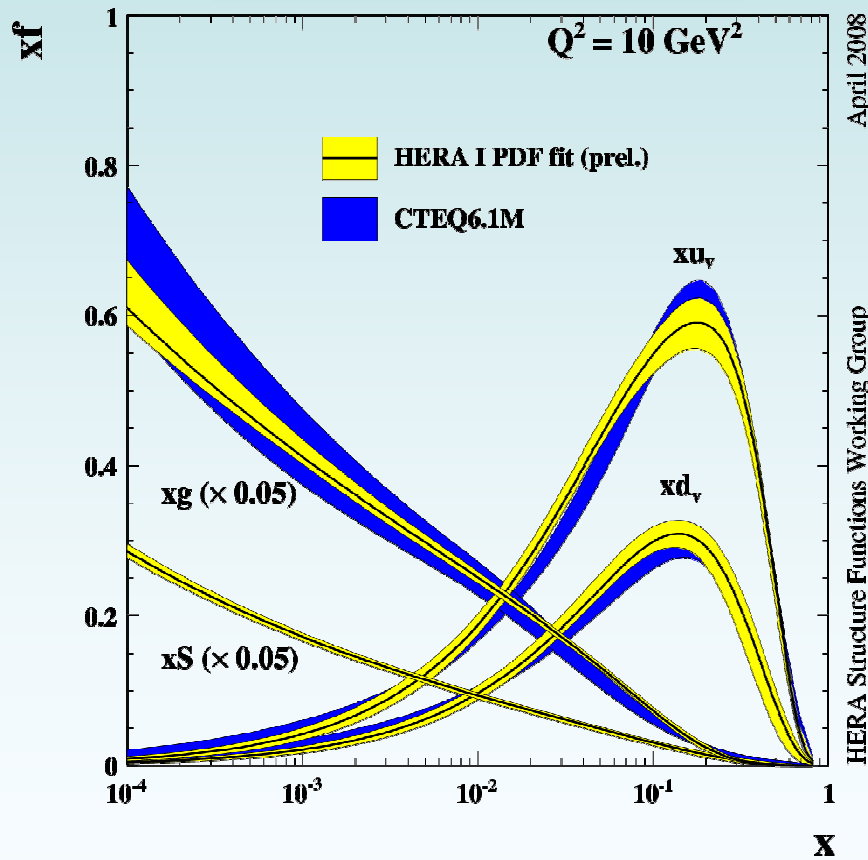
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# HERA PDF vs. Global fits

Comparison with older CTEQ and MSTW PDFs

## Caution:

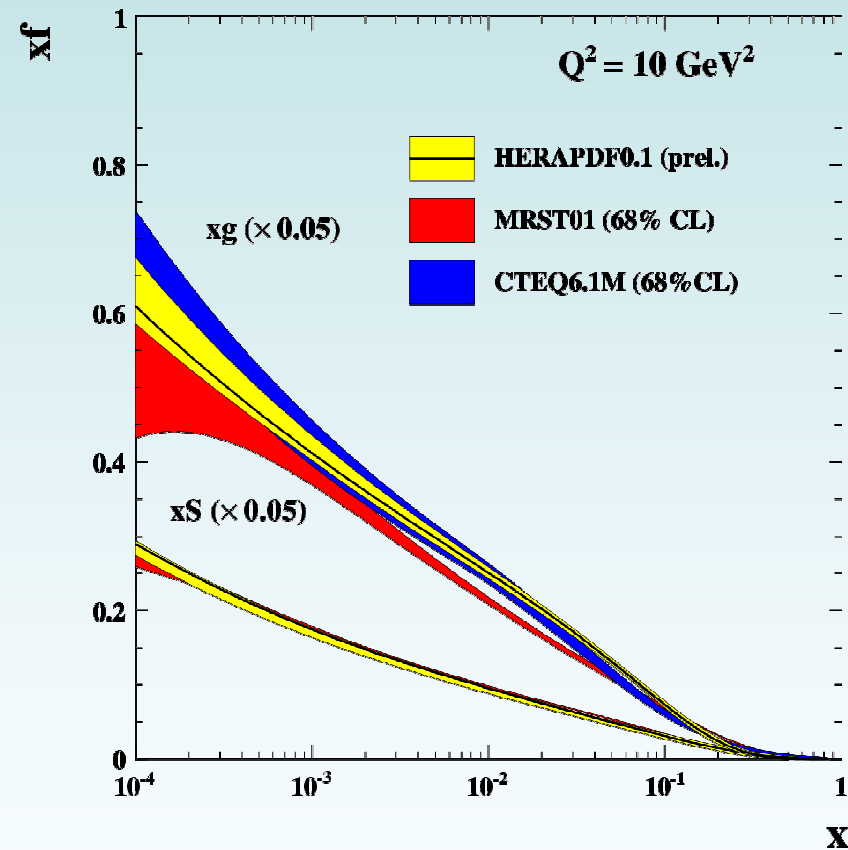
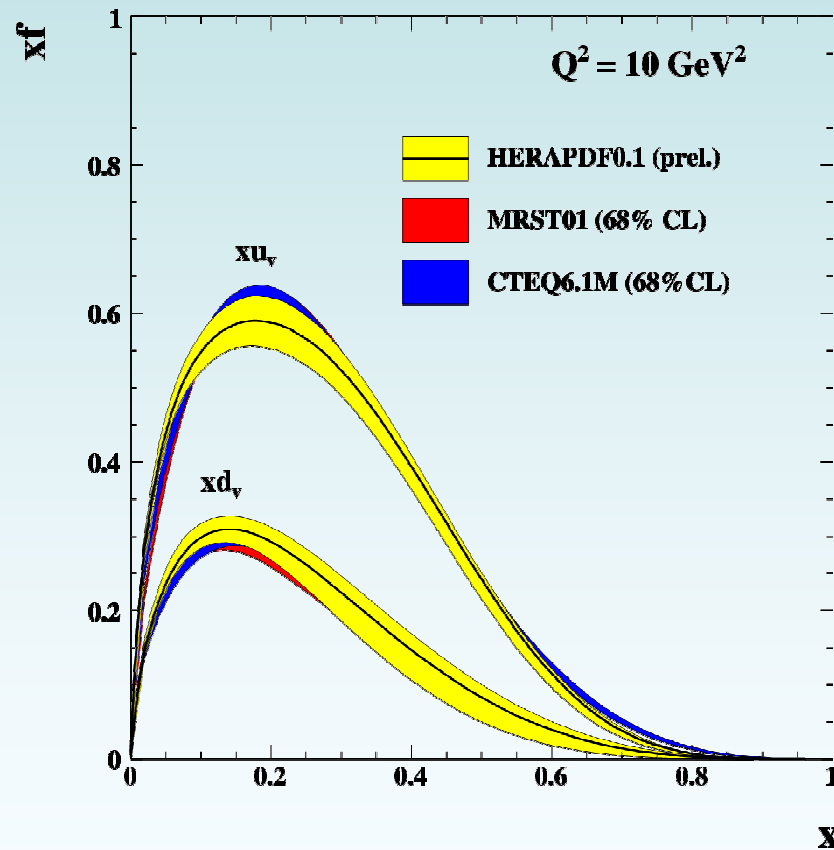
- Different  $\Delta X^2$ 's ... also:
- global fits: 90% CL
- HERA fit: 68% CL



# HERA PDF vs. Global fits

Comparison with older CTEQ and MSTW PDFs

68% CL

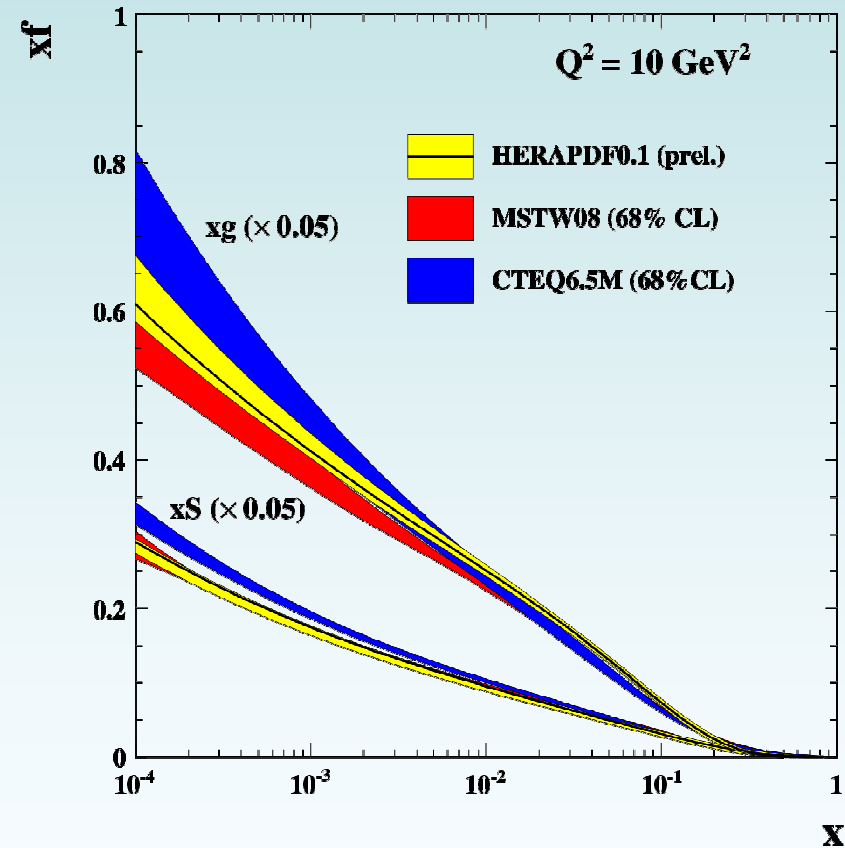
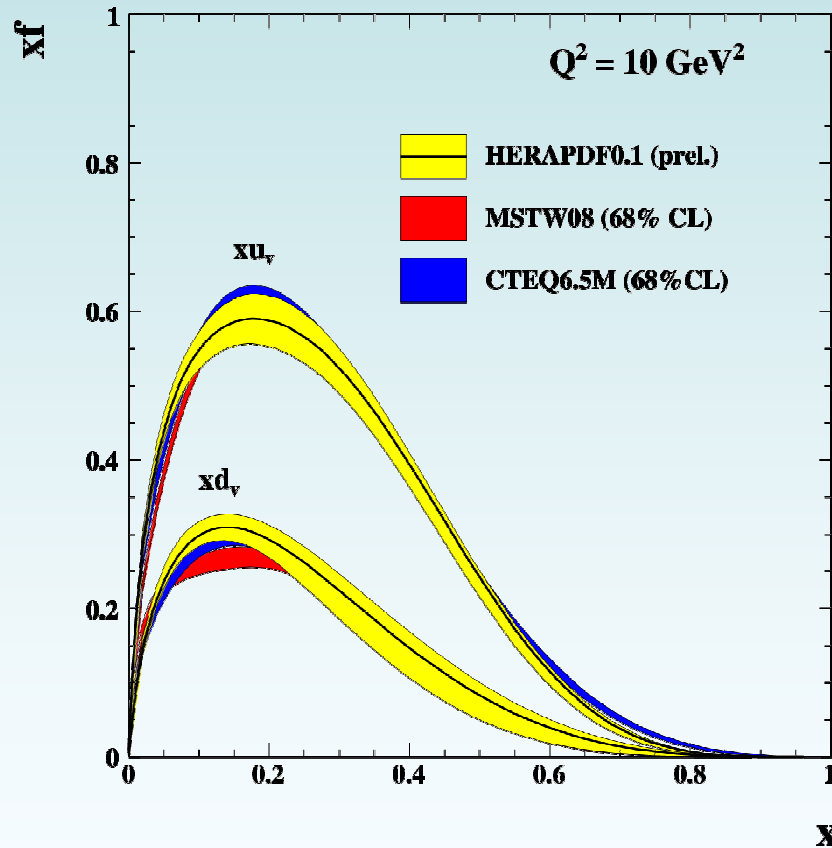


global fits scaled by 1.64485 [NB. HERA PDF includes exp. and model uncertainties]

# HERA PDF vs. Global fits

Comparison with recent CTEQ and MSTW PDFs

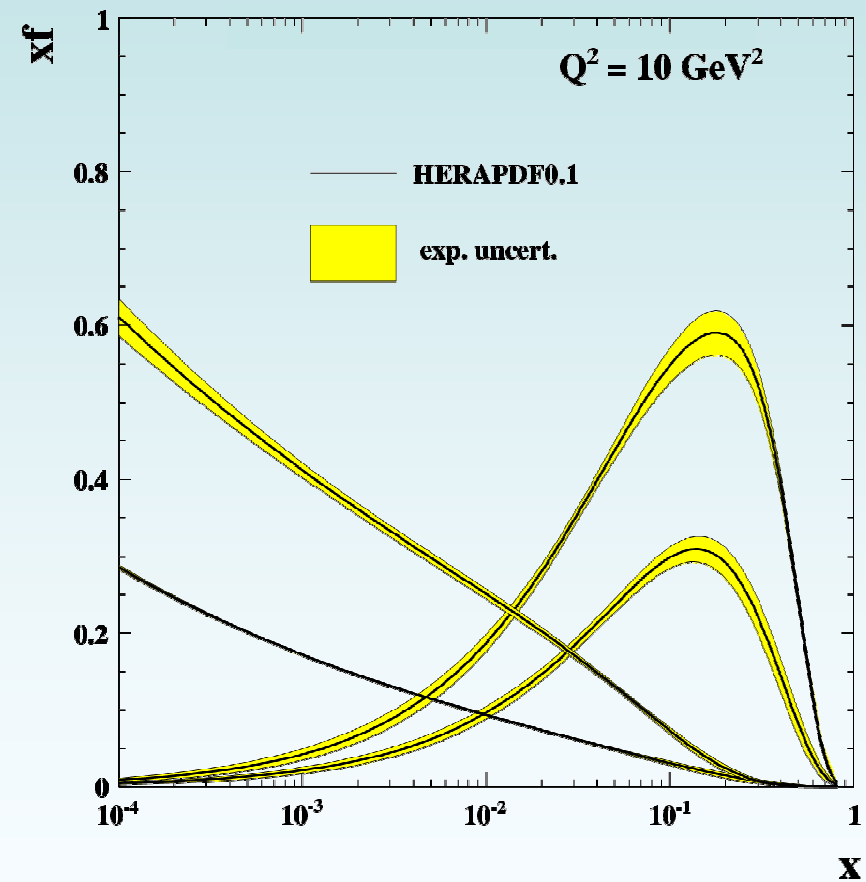
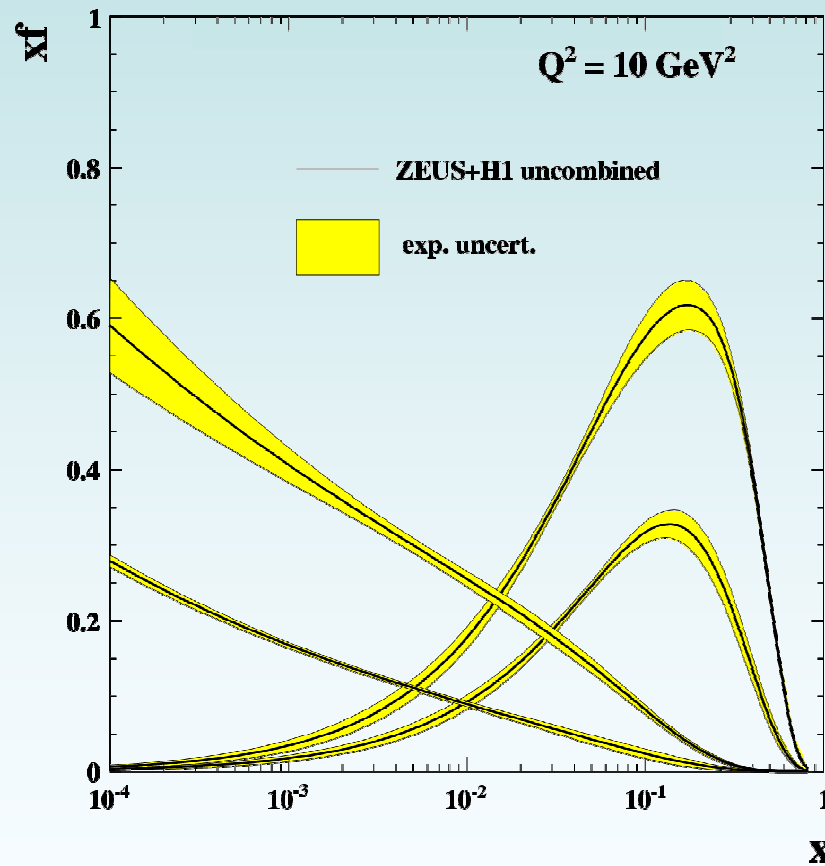
68% CL



global fits scaled by 1.64485 [NB. HERA PDF includes exp. and model uncertainties]

# HERA PDF: checks

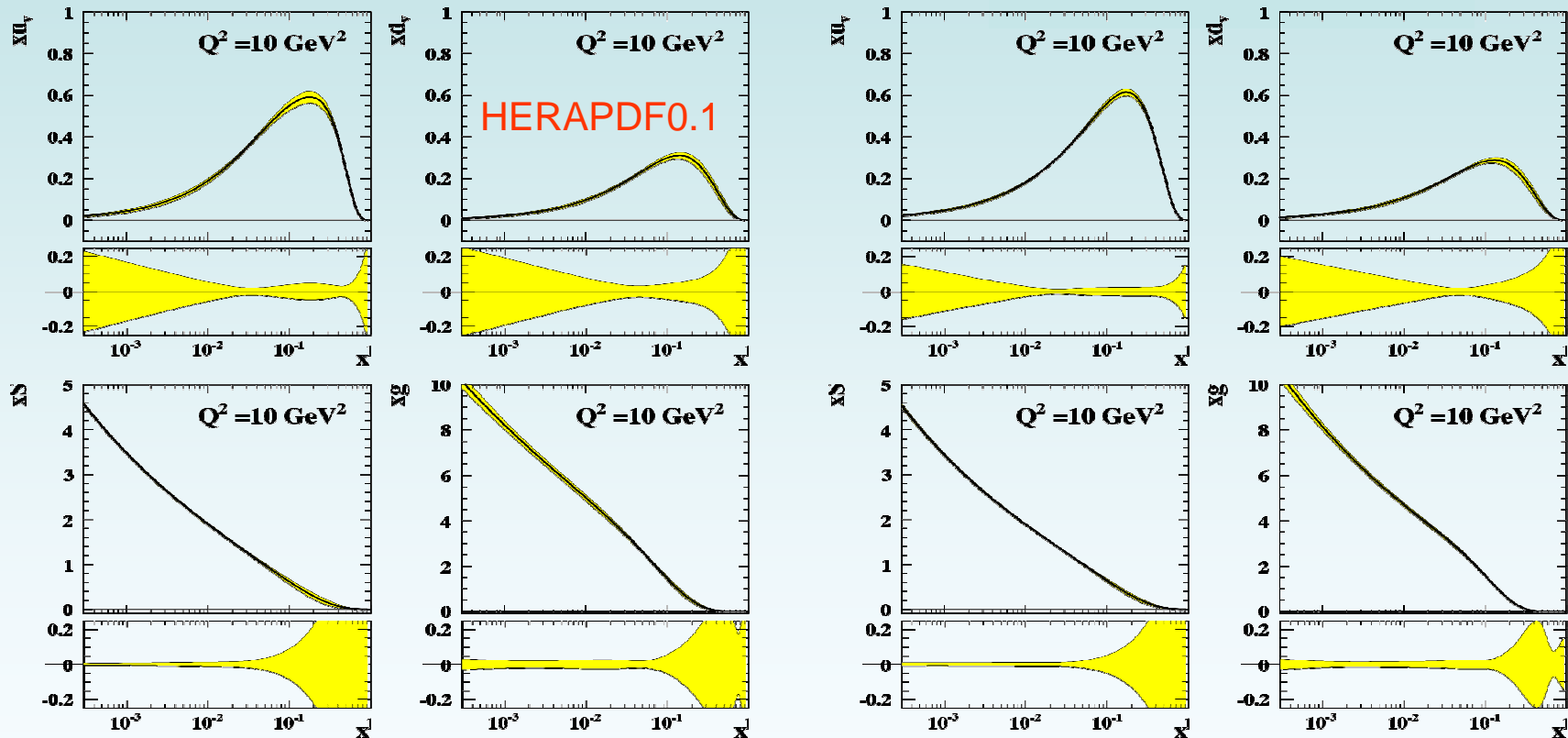
Comparison with fit to H1+ZEUS (uncombined)



Same parameterisation and assumptions in both fits

# HERA PDF: checks

## Comparison of uncertainties for different treatments



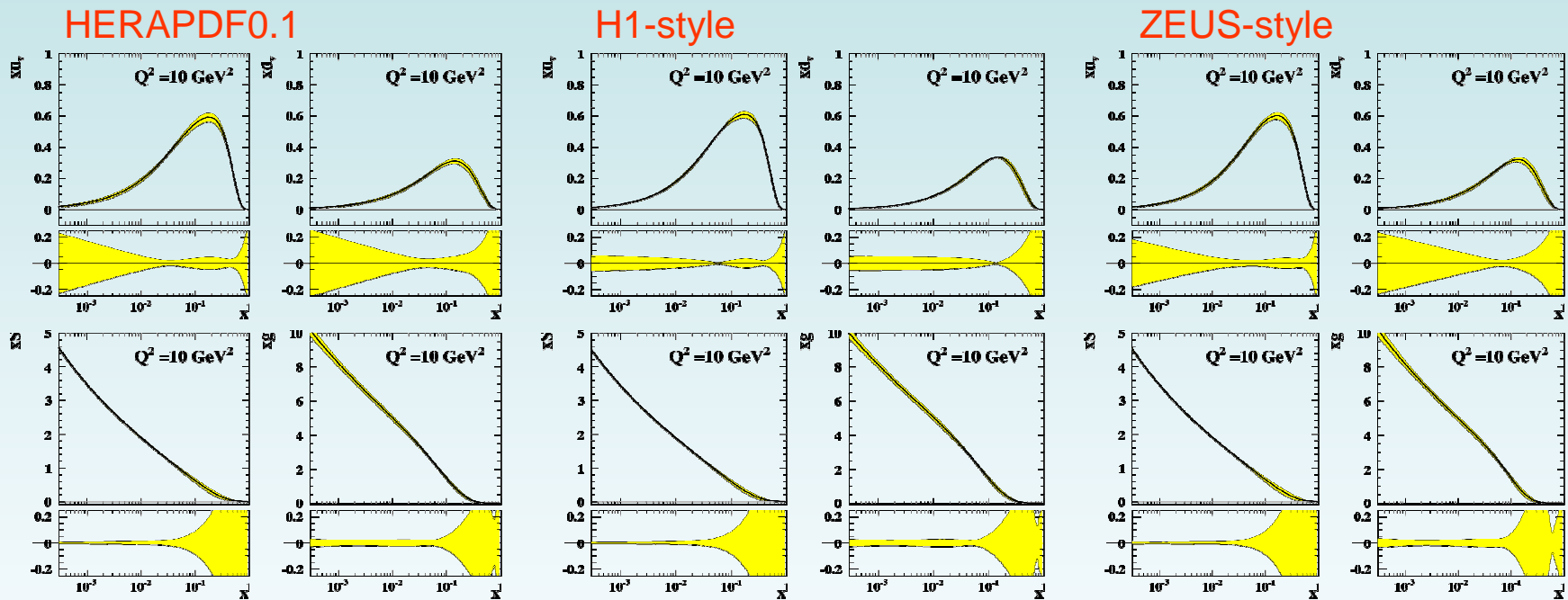
43 data systematics in quadrature  $\uparrow$   
+ offset 4 procedural uncertainties

$\uparrow$  treat all 47 systs. as correlated



# HERA PDF: checks

Comparison of uncertainties with different parameterisations



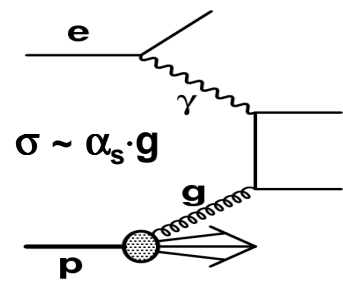
PDF uncertainties (experimental only) from different parameterisations:  
HERAPDF0.1 (left), H1-style (centre), ZEUS-style (right)

# HERA and PDFs: a rough guide

NC DIS: 
$$\tilde{\sigma}^{\pm} = \frac{d^2\sigma^{\pm}}{dx dQ^2} \frac{Q^4 x}{2\pi\alpha^2 Y_{\pm}} = \tilde{F}_2^{\pm} \mp \frac{Y_{-}}{Y_{+}} x \tilde{F}_3^{\pm} - \frac{y^2}{Y_{+}} \tilde{F}_L^{\pm}$$

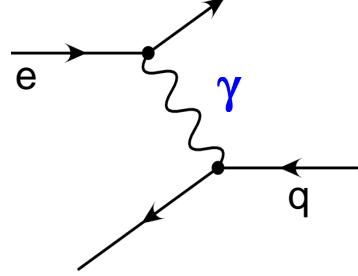
## Final States:

(Jets, Charm, ...)

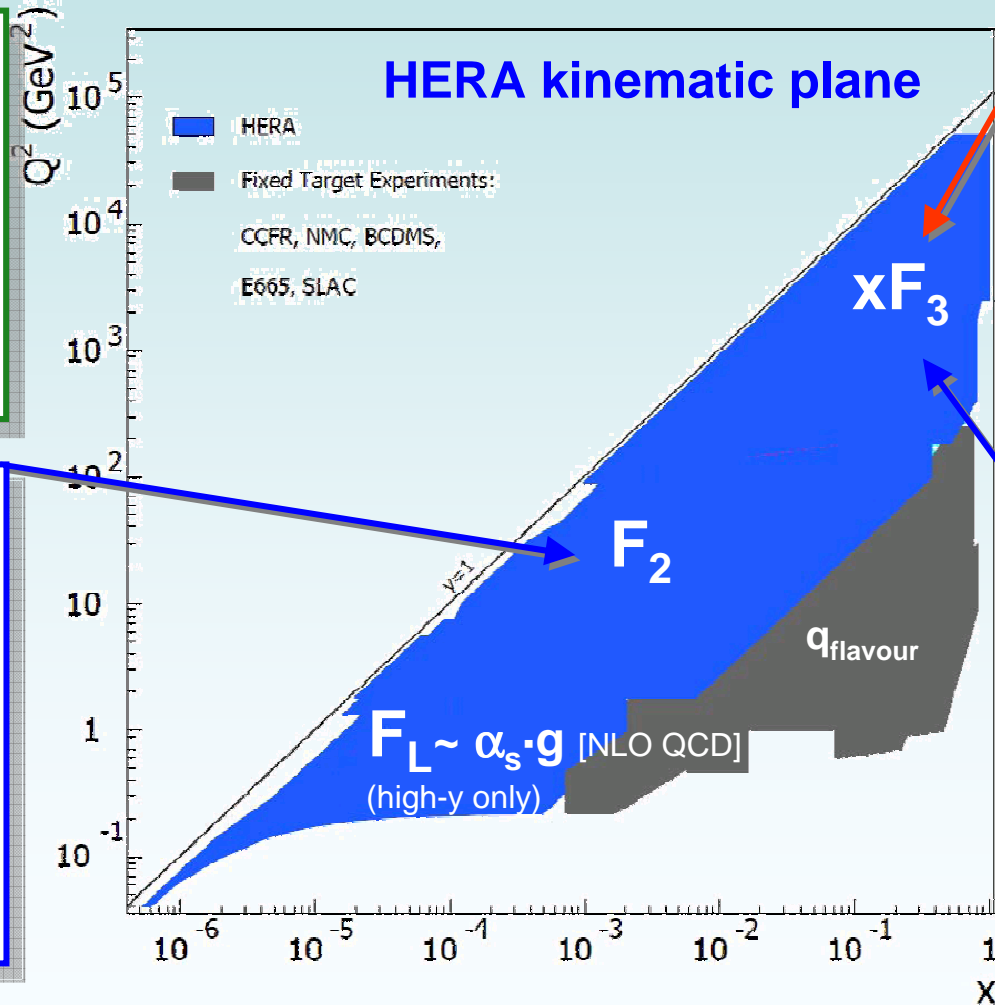


## Low $Q^2$ NC

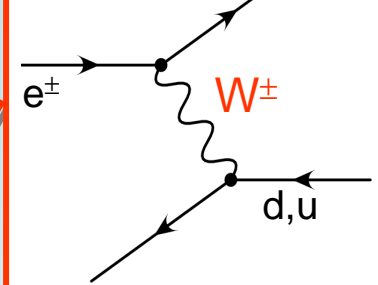
( $\gamma$  exchange)



$F_2 \sim \sum x (q + qbar)$   
 $dF_2/d\ln Q^2 \sim \alpha_s \cdot g$

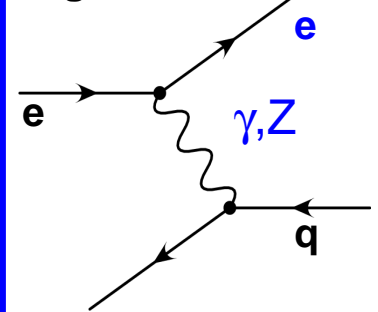


## CC



flavour composition  
 $e^+$ : d  $e^-$ : u

## High $Q^2$ NC



$x F_3 \sim \sum x (q - qbar)$   
 valence