DIS 2010

XVIII INTERNATIONAL WORKSHOP ON DEEP-INELASTIC SCATTERING AND RELATED SUBJECTS

Combined Measurement and QCD Analysis of the Inclusive ep Scattering Cross Sections at HERA

[Published in JHEP 1001:109,2010]

SHIRAZ HABIB

on behalf of the H1 *and* ZEUS *Collaborations*

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Outline:

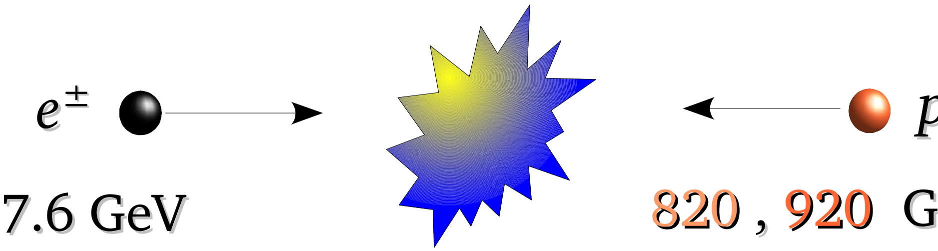
- HERA Collider and the H1 & ZEUS Detectors
- Combining the H1 & ZEUS Measurements
- HERAPDF1.0 QCD Fit – PDF Determination
- Summary

HERA Collider and the H1 & ZEUS Detectors

HERA : A 6.3 km $e^{\pm}p$ collider located in Hamburg, Germany.

2 Phases of HERA Running [I + II]

HERA I [1992 – 2000]



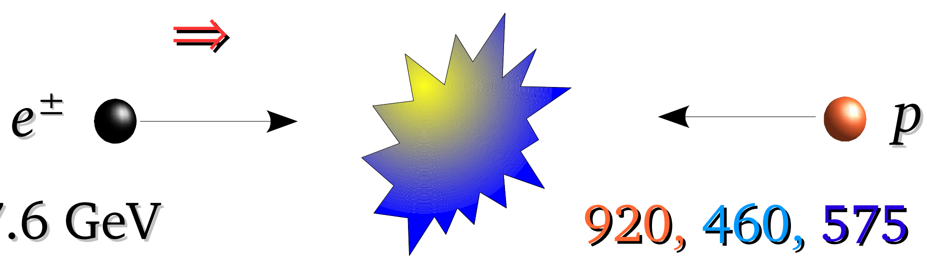
27.6 GeV

820 , 920 GeV

$\sqrt{s}$ = 301 , 319 GeV

HERA II [2003 – 2007]

⇒



27.6 GeV

920, 460, 575 GeV

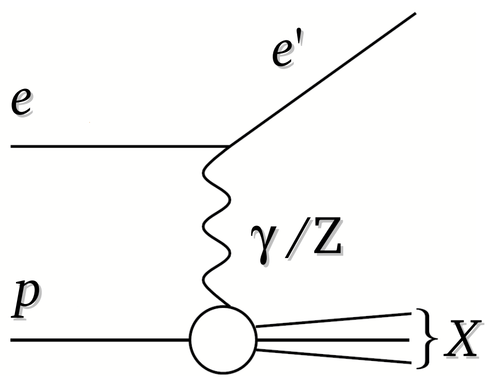
$\sqrt{s}$ = 319, 225, 252 GeV

Analyses presented in this talk use HERA I data only

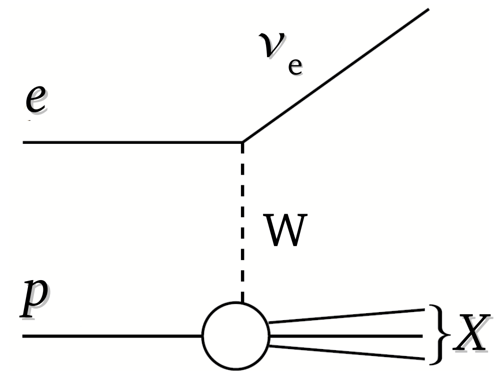
Colliding-Beam Experiments : **H1 & ZEUS**

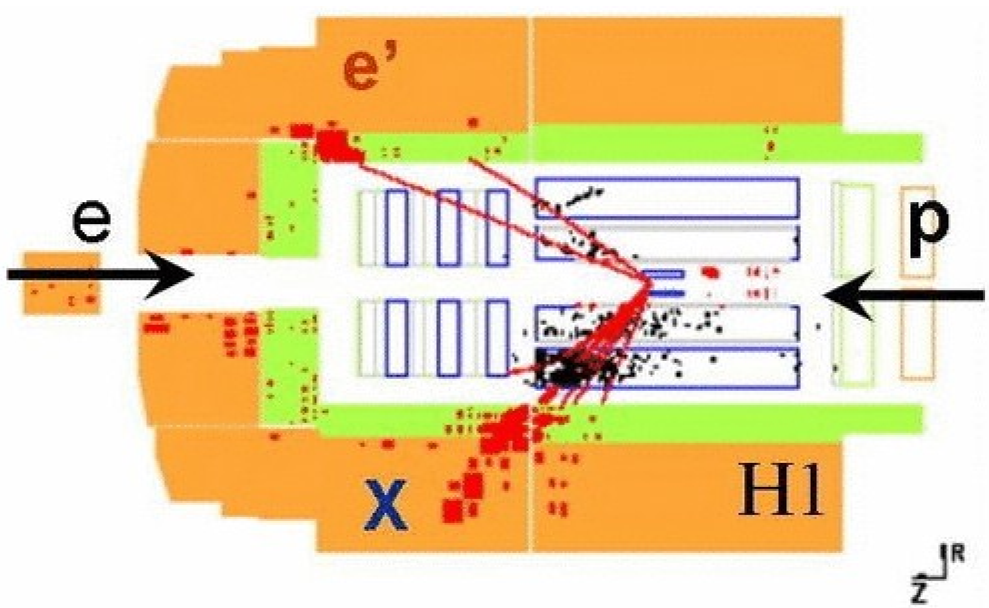
Inclusive Processes:

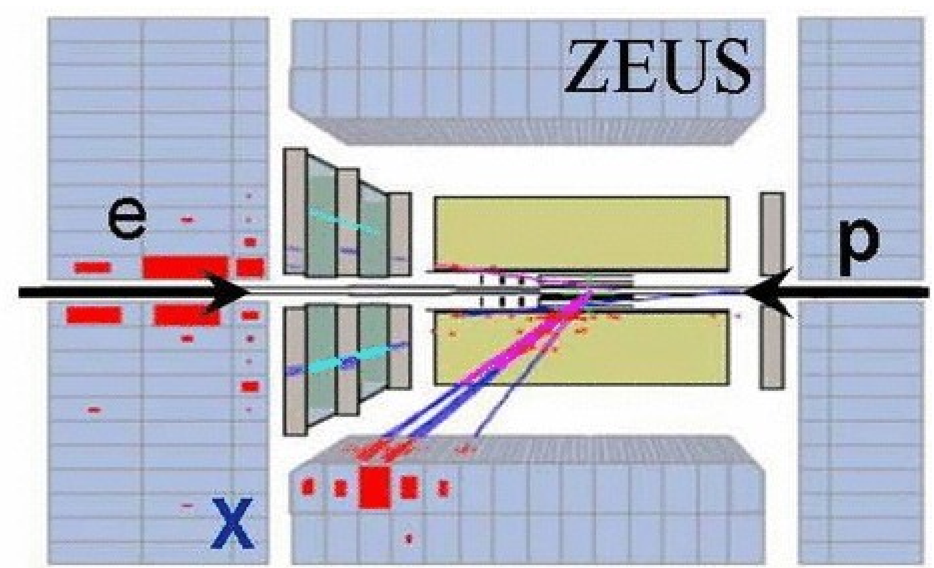
NC : $e\,p \rightarrow e'\,X$



CC : $e\,p \rightarrow \nu_e\,X$



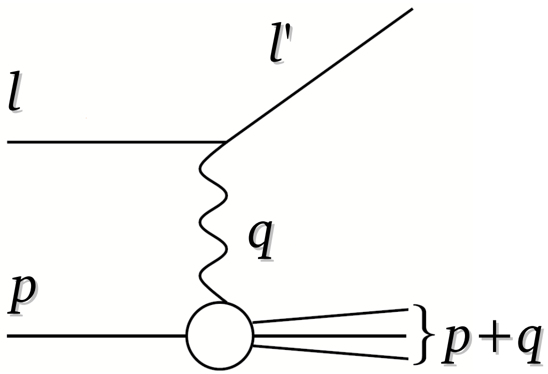




Colliding-Beam Experiments : H1 & ZEUS

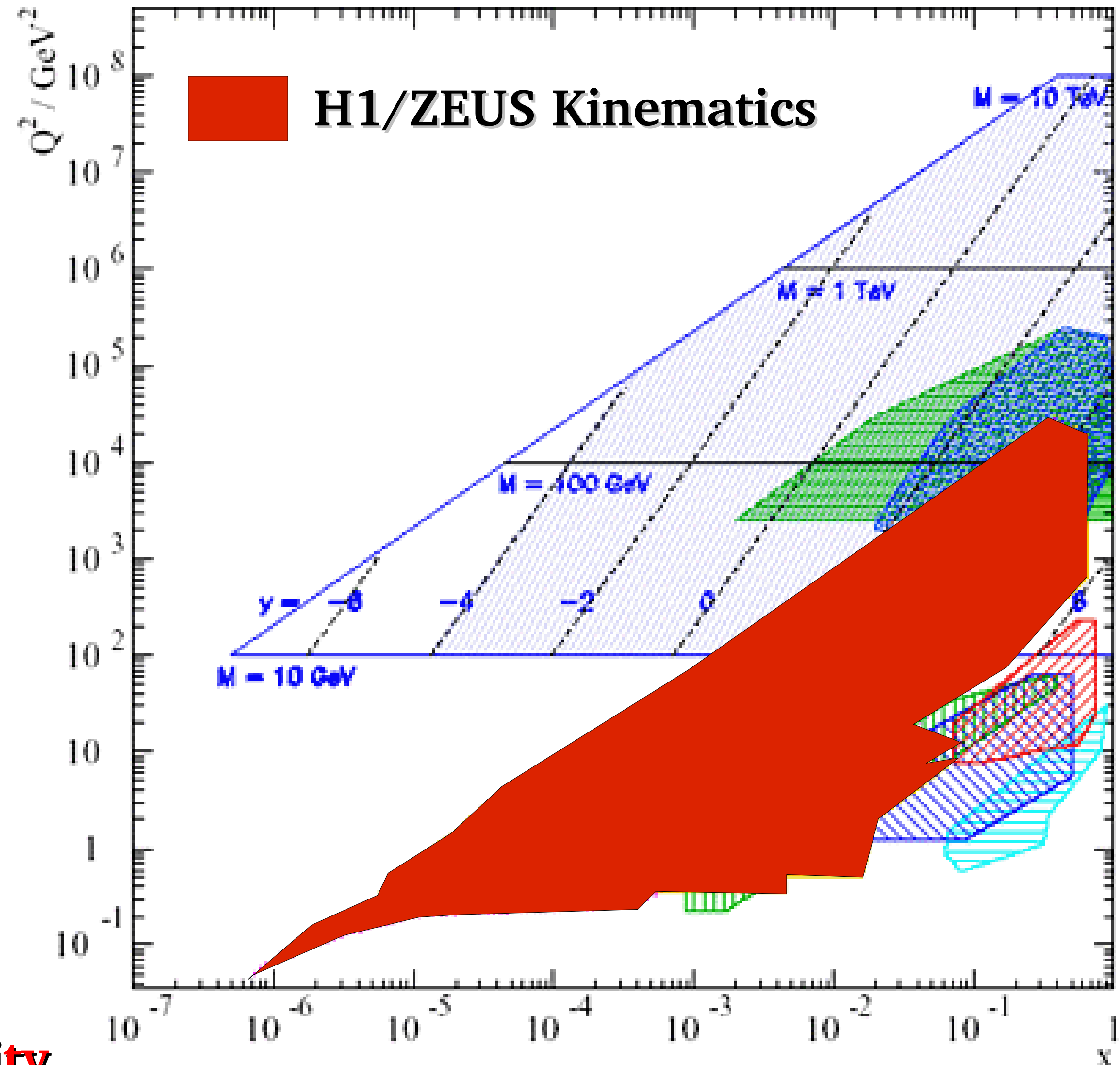
Inclusive Measurement:

$\sigma_{NC}(x,Q^2)$, $\sigma_{CC}(x,Q^2)$



$$Q^2 = -q^2$$
$$x = Q^2/(2p.q)$$

6 orders of magnitude in Q^2



HERA provides unique opportunity to study the proton.

6 orders of magnitude in *x*

Combining the H1 & ZEUS Measurements

Statistical Precision:

H1 & ZEUS collected *similar* amounts of data:

- 100 pb^{-1} of e^+p data
- 15 pb^{-1} of e^-p data

[HERA I]

A combined measurement should improve **statistical precision** : $\delta_{\text{stat}} \rightarrow 0.707\, \delta_{\text{stat}}$

Systematic Precision:

H1 and ZEUS are *different* detectors and use *different* analysis techniques:

- Calorimetry
- Kinematic Reconstruction

The H1 and ZEUS cross sections have different sensitivities to similar sources of correlated systematic uncertainty $\Rightarrow$ improve the **systematic precision**.

The combination method used to average our cross sections takes the uncorrelated errors as well as the systematic correlations into account.

Input: H1 & ZEUS published cross sections [Inclusive NC , CC $e^{\pm}p$].

Combination Method:

[1] ***Swim*** **H1 and ZEUS measurements to common grid (x,Q^2) :**

$$\sigma_{\mathrm{H1}}\left(x_{\mathrm{H1}}, Q^2_{\mathrm{H1}}\right) \rightarrow \sigma_{\mathrm{H1}}\left(x, Q^2\right) \quad ; \quad \sigma_{\mathrm{ZEUS}}\left(x_{\mathrm{ZEUS}}, Q^2_{\mathrm{ZEUS}}\right) \rightarrow \sigma_{\mathrm{ZEUS}}\left(x, Q^2\right)$$

Input: H1 & ZEUS published cross sections [Inclusive NC , CC $e^{\pm}p$].

Combination Method:

[1] *Swim* H1 and ZEUS measurements to common grid (x,Q^2) :

$$\sigma_{H1}\left(x_{H1}, Q^2_{H1}\right) \rightarrow \sigma_{H1}(x,Q^2) \quad ; \quad \sigma_{ZEUS}\left(x_{ZEUS}, Q^2_{ZEUS}\right) \rightarrow \sigma_{ZEUS}(x,Q^2)$$

[2] **For CC and NC [y<0.35] :** $\sigma_{820} \rightarrow \sigma_{920}$

Input: H1 & ZEUS published cross sections [Inclusive NC , CC $e^{\pm}p$].

Combination Method:

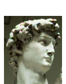
[1] *Swim* H1 and ZEUS measurements to common grid (x,Q^2) :

$$\sigma_{\mathrm{H1}}\left(x_{\mathrm{H1}}, Q^2{}_{\mathrm{H1}}\right) \rightarrow \sigma_{\mathrm{H1}}(x,Q^2) \quad ; \quad \sigma_{\mathrm{ZEUS}}\left(x_{\mathrm{ZEUS}}, Q^2{}_{\mathrm{ZEUS}}\right) \rightarrow \sigma_{\mathrm{ZEUS}}(x,Q^2)$$

[2] For CC and NC [$y<0.35$] : $\sigma_{820} \rightarrow \sigma_{920}$

[3] **Build a χ^2 function for each data-set, *exp*:**

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



Input: H1 & ZEUS published cross sections [Inclusive NC , CC $e^{\pm}p$].

Combination Method:

[1] *Swim* H1 and ZEUS measurements to common grid (x,Q^2) :

$$\sigma_{H1}\left(x_{H1}, Q^2_{H1}\right) \rightarrow \sigma_{H1}(x,Q^2) \quad ; \quad \sigma_{ZEUS}\left(x_{ZEUS}, Q^2_{ZEUS}\right) \rightarrow \sigma_{ZEUS}(x,Q^2)$$

[2] For CC and NC [$y<0.35$] : $\sigma_{820} \rightarrow \sigma_{920}$

[3] **Build a χ^2 function for each data-set, *exp*:**

Combination at point i
*[Estimate of 1 **true cross section**]*

Measurement at point i

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

***Sensitivity** of the cross section to the j^{th} source of **correlated** uncertainty.*

*Shift of the j^{th} source of **correlated** uncertainty*

γ^i_j *defined as the relative change of the measurement for a 1 sigma shift of the error source*

$\delta_{i,\mathrm{stat}} / \delta_{i,\mathrm{uncor}}$ *Relative stat. / syst. error on the measurement*

[4] **Build a total χ^2 for all data sets:** $\chi^2_{\text{tot}} = \sum_{\text{exp}} \chi^2_{\text{exp}}$

[5] **Minimize χ^2_{tot}**

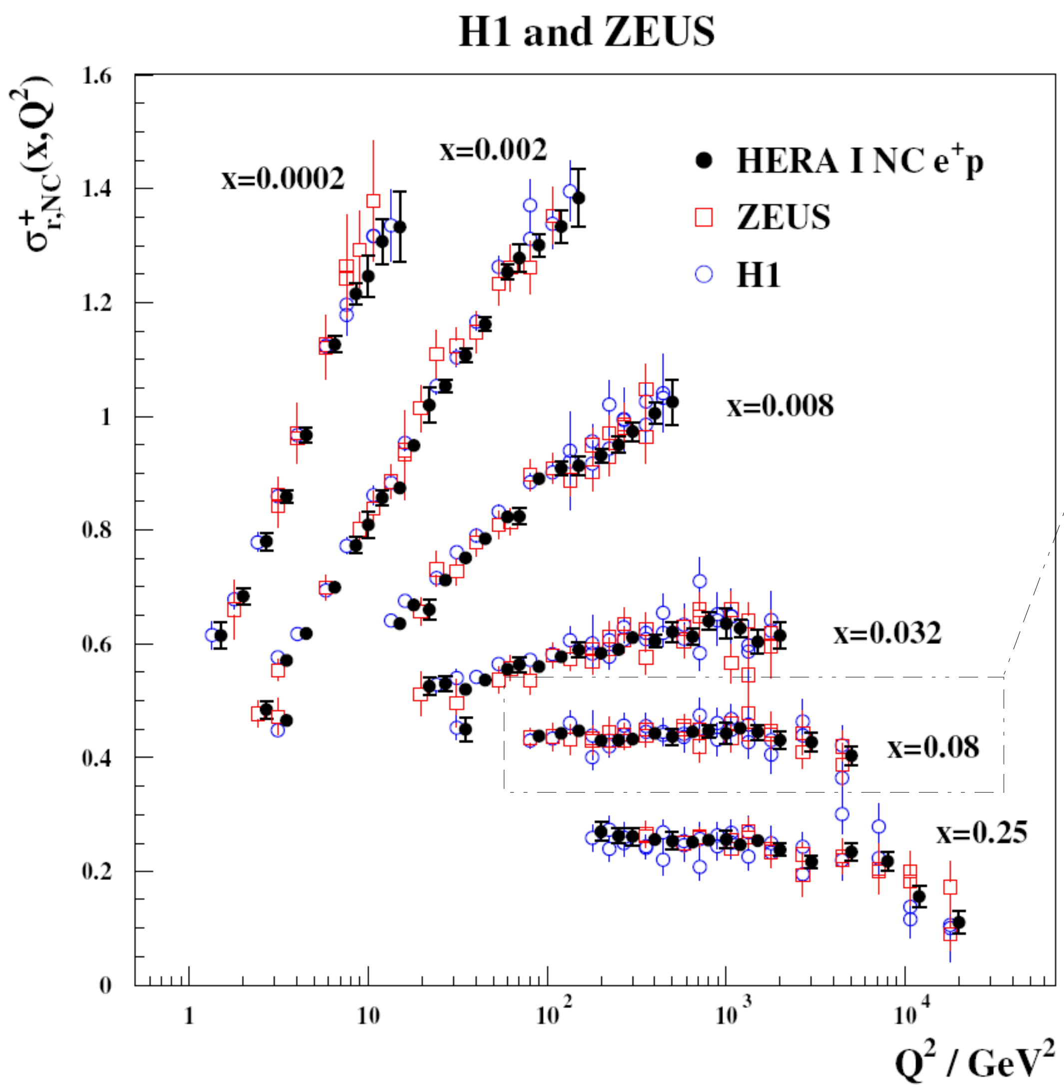
Notes:

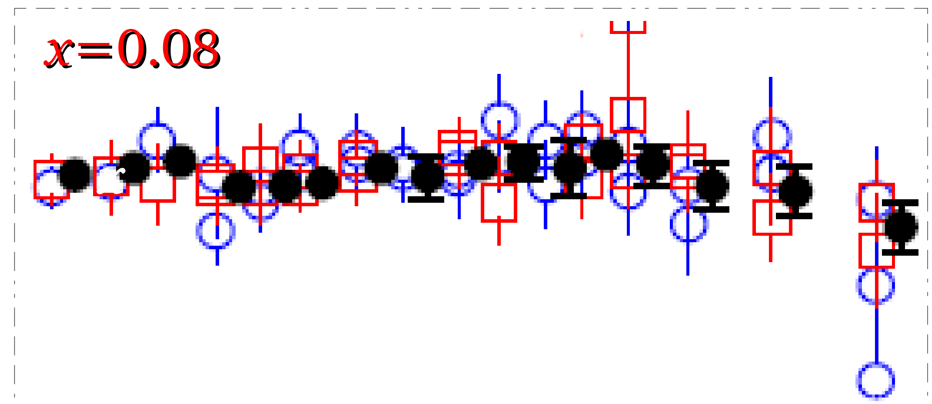
*[1] **Additive** instead of **multiplicative** error treatment added as an extra "procedural uncertainty". Typically less than 0.5%.*

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

*[2] Only correlation assumed **between H1 and ZEUS** is due to normalization. Other correlations between the experiments which contribute significantly are due to **background estimation** [significant only at high y] and **hadron energy scale**. Added as procedural uncertainties. Can be a few %.*

- **1402** measurements with **110** correlated sources of uncertainty combined to **741** cross sections.
- **χ^2 / dof = 636.5 / 656** ; No tension in Pulls ; $|b_j| < 2$ ⇒ **H1 and ZEUS Agree!**





Systematic Uncertainty:

- $\delta_{\text{H1 LAR}} \rightarrow 0.45\ \delta_{\text{H1 LAR}}$
- $\delta_{\text{ZEUS BG}} \rightarrow 0.35\ \delta_{\text{ZEUS BG}}$

Overall Precision:

- 2% for $3<Q^2<500$ GeV^2
- 1% for $2<Q^2<100$ GeV^2

HERAPDF1.0 QCD Fit – PDF Determination

Data Input:

The HERA Inclusive Combined Cross Sections [NC, CC, $e^{\pm}p$] is a **Consistent Data Set** which allows the extraction of valence, sea quark and gluon (scaling violation).

Model:

PDF evolution	:	$Q_0^2 = 1.9\ \mathrm{GeV}^2$ use DGLAP @ NLO
Renormalization & Factorization scale	:	Q^2
m_c	:	1.4 GeV
m_b	:	4.75 GeV
$\alpha_s(M_z)$	:	0.1176
Q^2_{min} of Data	:	$3.5\ \mathrm{GeV}^2$
$f_s = \bar{s} / (\bar{s}+\bar{d})$ @ Q_0^2	:	0.31
Heavy Quark Coefficient Functions	:	GMVFNS Robert Thorne VFNS 2008

Parameterization *xf(x)*:

- Use General form $x\,f(x) = A\,x^{B}\,(1\text{-}x)^{C}$: $xg(x)$; $xu_v(x)$; $xd_v(x)$; $x\bar{U}(x)$; $x\bar{D}(x)$
  and fit ⇒ χ^2_9.

- Modify $xf(x)$: $xf(x) \rightarrow x f(x)\,(1 + \epsilon x^{1/2} + Dx + Ex^2)$
  and fit ⇒ χ^2_{10}. Find ϵ, D, E that gives best 10 parameter fit ⇒ E_{u_v}

- Repeat to find best 11 parameter fit. Find that χ^2 is saturated.
  Settle for **10 parameter fit**:

$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g}, \\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1 + E_{u_v}x^2\right), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}, \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}, \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.
\end{aligned}
$$

Additional Contraints:

- Quark Number Sum Rules
- Momentum Sum Rule
- $B_{\bar{U}} = B_{\bar{D}}$ & $A_{\bar{U}} = A_{\bar{D}}\,(1\text{-}f_s)$
  $\bar{u} \rightarrow \bar{d}$ as $x \rightarrow 0$
- $B_{u_v} = B_{d_v}$

PDF Uncertainties : Experimental ⊕ Model ⊕ Parameterization

Experimental Uncertainties:

Consistent NC, CC, $e^{\pm}p$ Data Sets ⇒ Use conventional tolerance : $\Delta\chi^2 = 1$
110 corr. syst. Uncertainties ⇒ Added in quadrature
Procedural Uncertainties ⇒ Use offset method

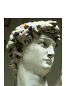
Model Uncertainties : f_s , m_c , m_b , Q^2_{min}

Variation	Standard Value	Lower Limit	Upper Limit
f_s	0.31	0.23	0.38
m_c [GeV]	1.4	1.35	1.65
m_b [GeV]	4.75	4.3	5.0
Q^2_{min} [GeV^2]	3.5	2.5	5.0
Q^2_0 [GeV^2]	1.9	1.5	2.5

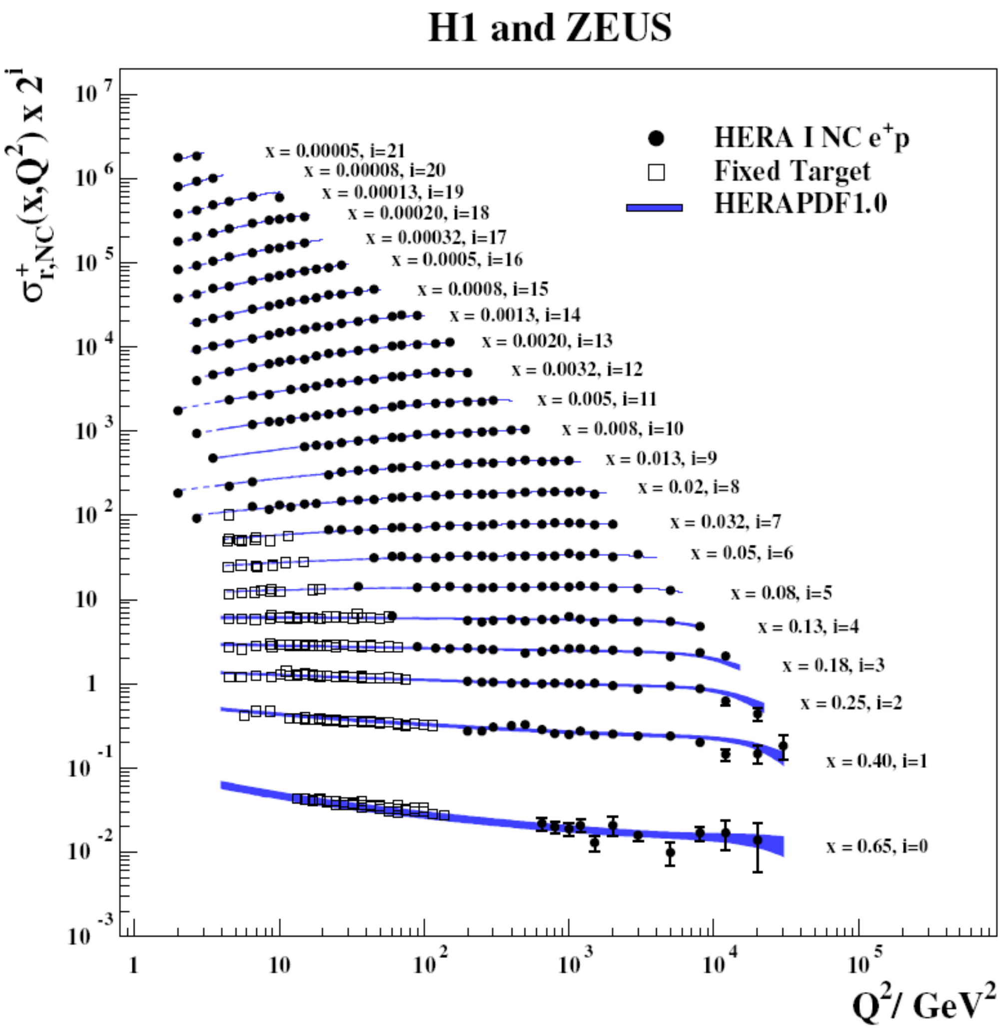
Parameterization Uncertainties :

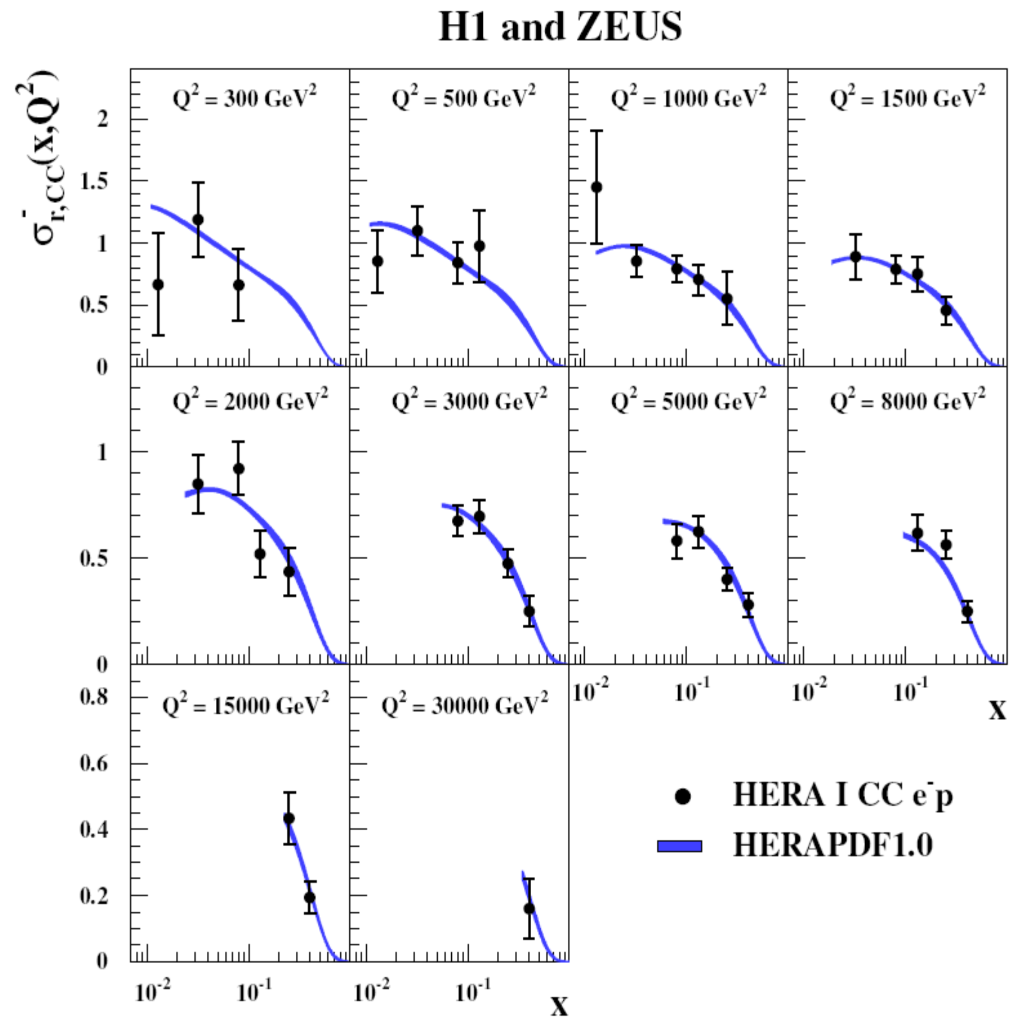
- Vary Q_0^2 and allow for negative gluon at its lower limit
- Relax $B_{u_v} = B_{d_v}$ constraint
- Variations of 11 parameter fits

} Uncertainty = Envelope of all Variations



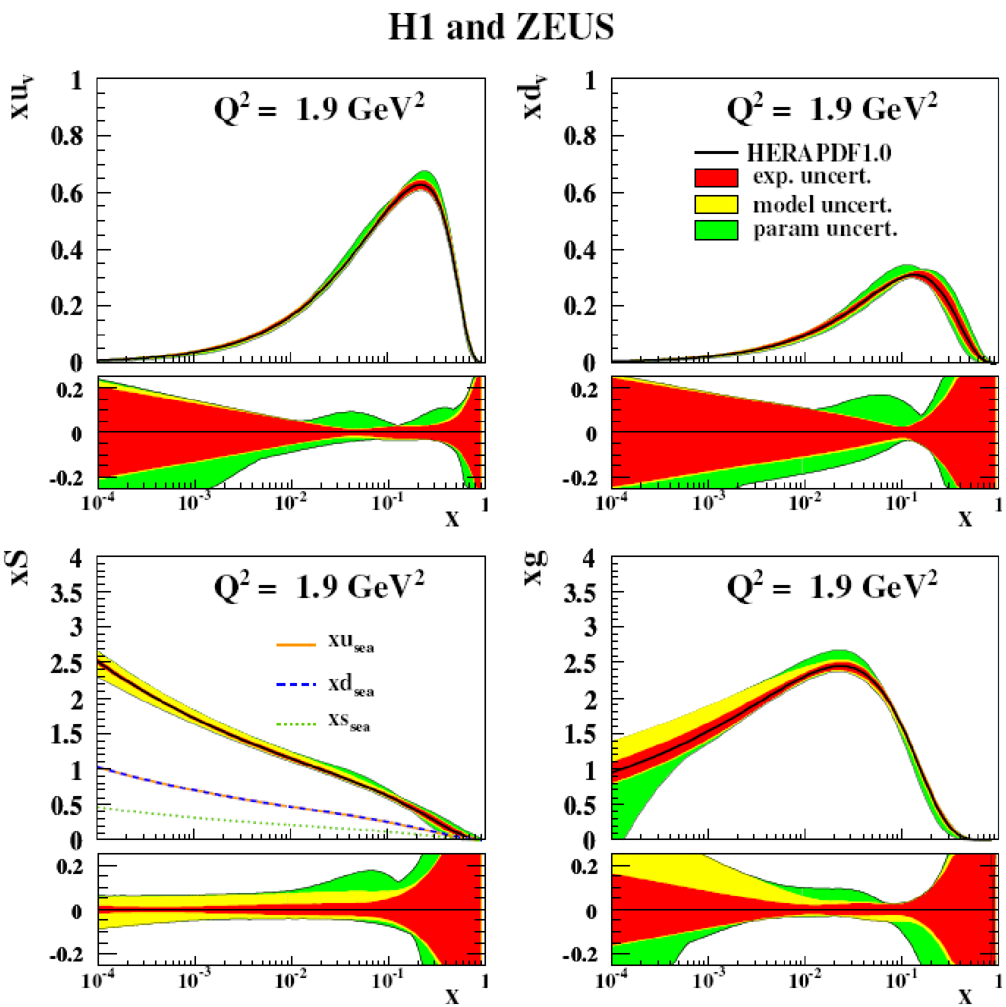
Good χ^2 / dof = 574 / 582





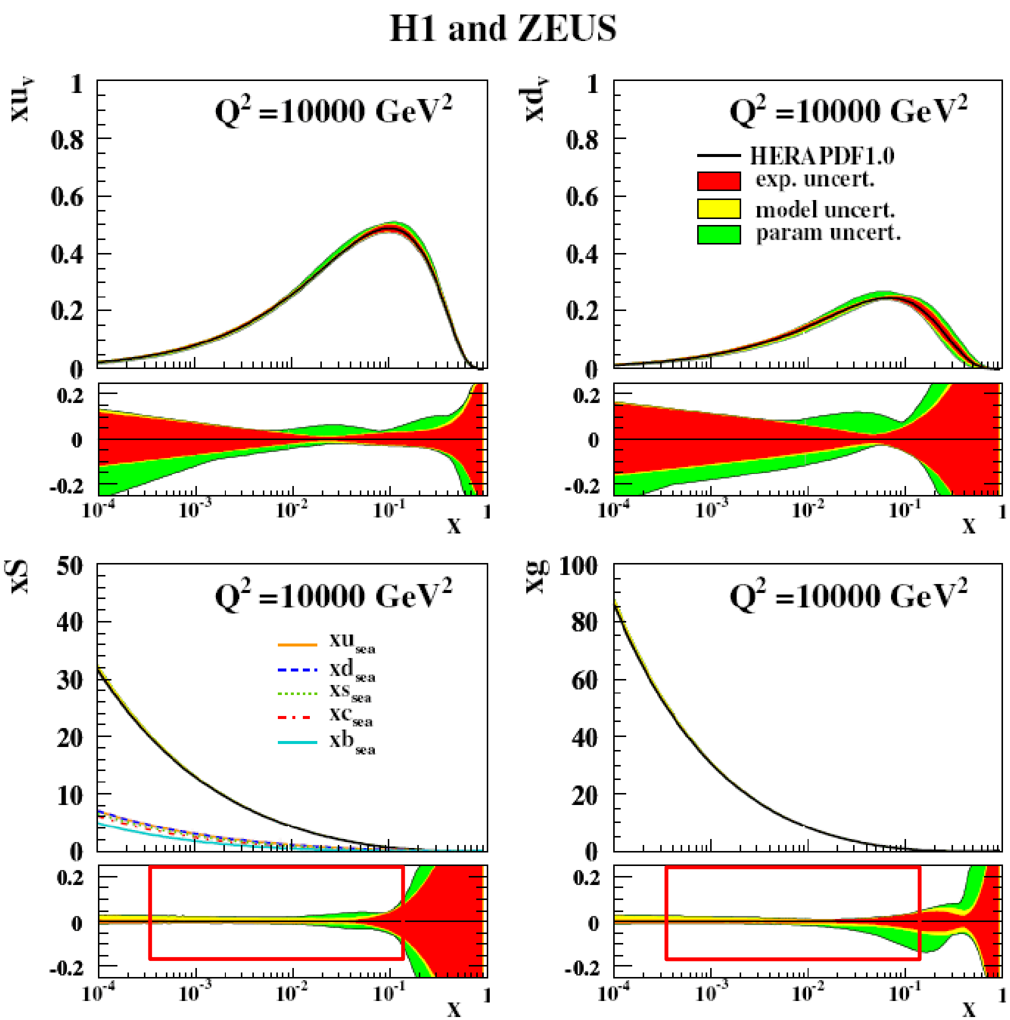
HERA and Fixed Target Data well described by HERAPDF1.0

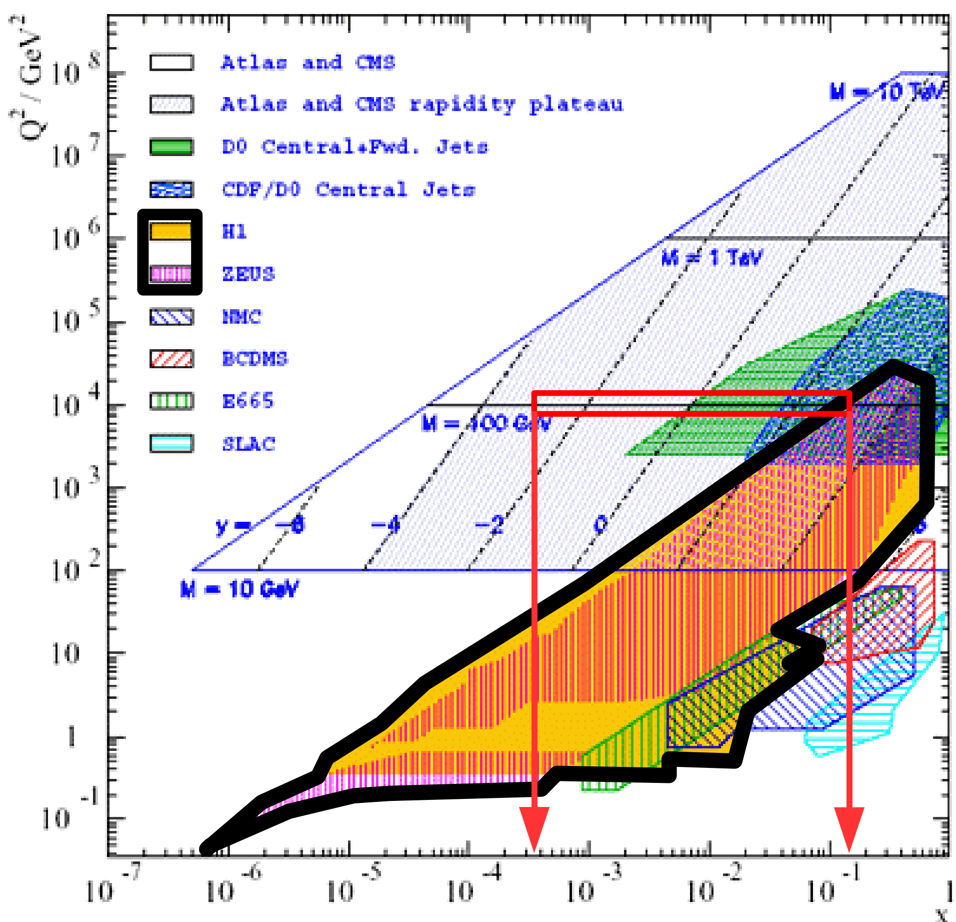
Starting Scale $Q^2 = 1.9\ GeV^2$



For the sea and gluon experimental uncertainties are relatively small.

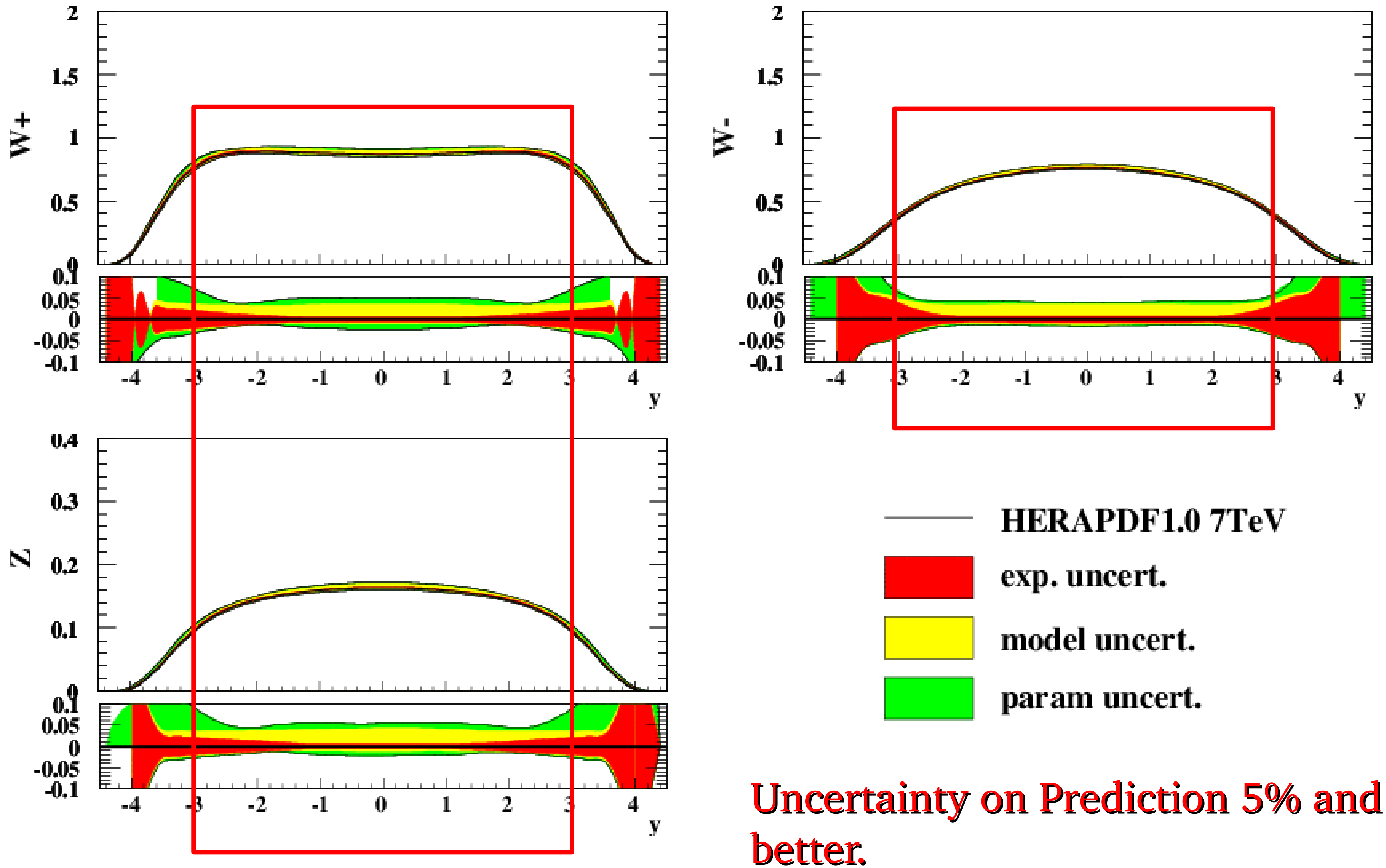
Evolve to $Q^2 = 10000\ GeV^2$





Few % uncertainty

W and Z Rapidity Distributions at LHC [7 TeV]
[Amanda Cooper-Sarkar]



Uncertainty on Prediction 5% and better.

Summary & The Shape of Things to Come …

- **H1 and ZEUS have combined their HERA I data resulting in improved precision [1% in best measured region : NC $20<Q^2<100$ GeV^2]**

- **An NLO QCD Fit to the combined measurement gives the HERAPDF1.0 PDFs with precision at the level of few % in low *x* region.**

- **New Data [Here at DIS 2010]:**
  - **HERA II 460/575 GeV NC (F_L) [*J. Grebenyuk, V. Radescu*]**
  - **HERA I/II F_2 charm [*R. Plačakyte / A. Cooper-Sarkar*]**

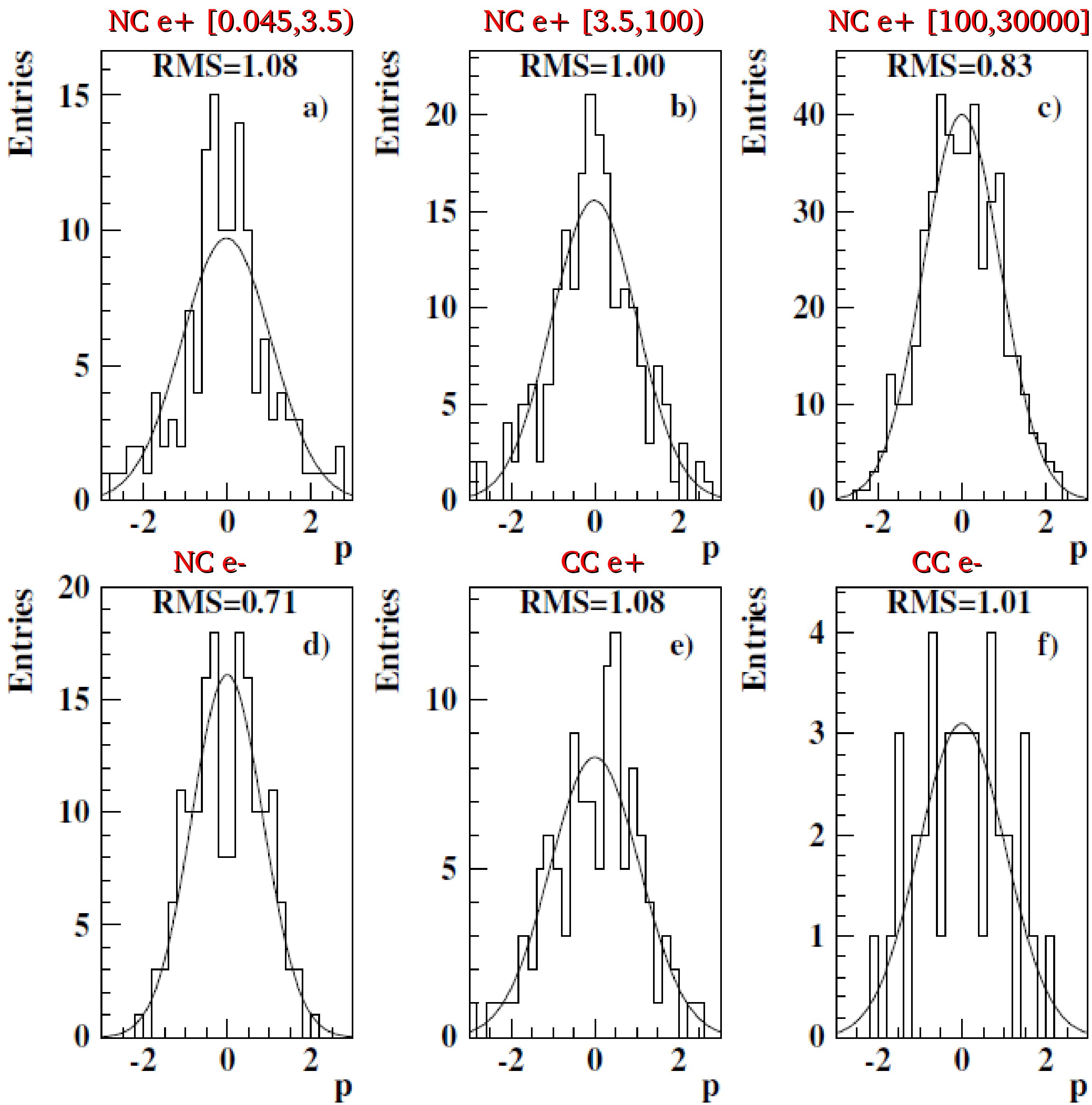
- **New Data:**
  - **HERA II NC, CC Inclusive**
  - **Jet Data**

More to come …

Thanks!

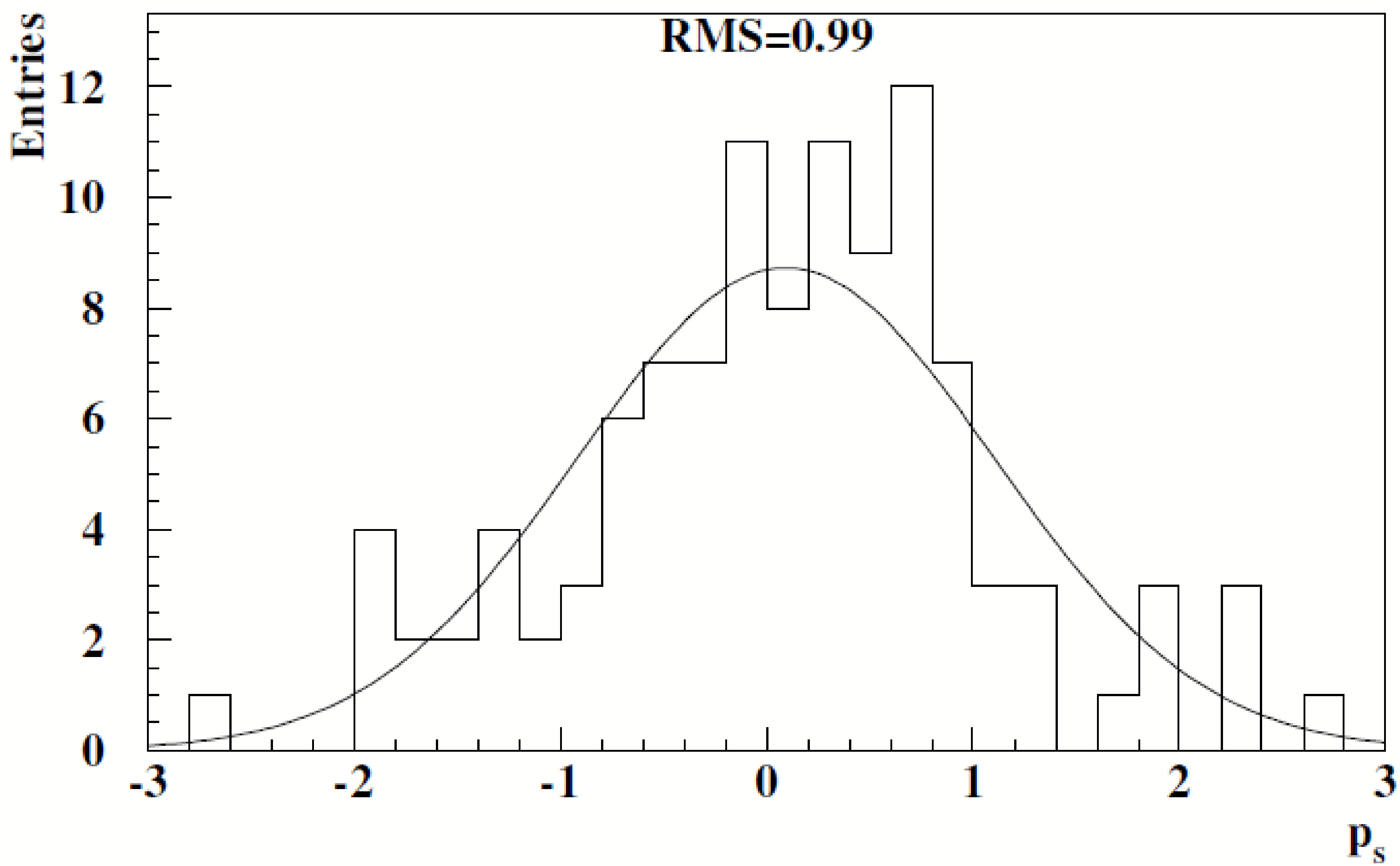
Backup

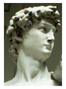
Pulls



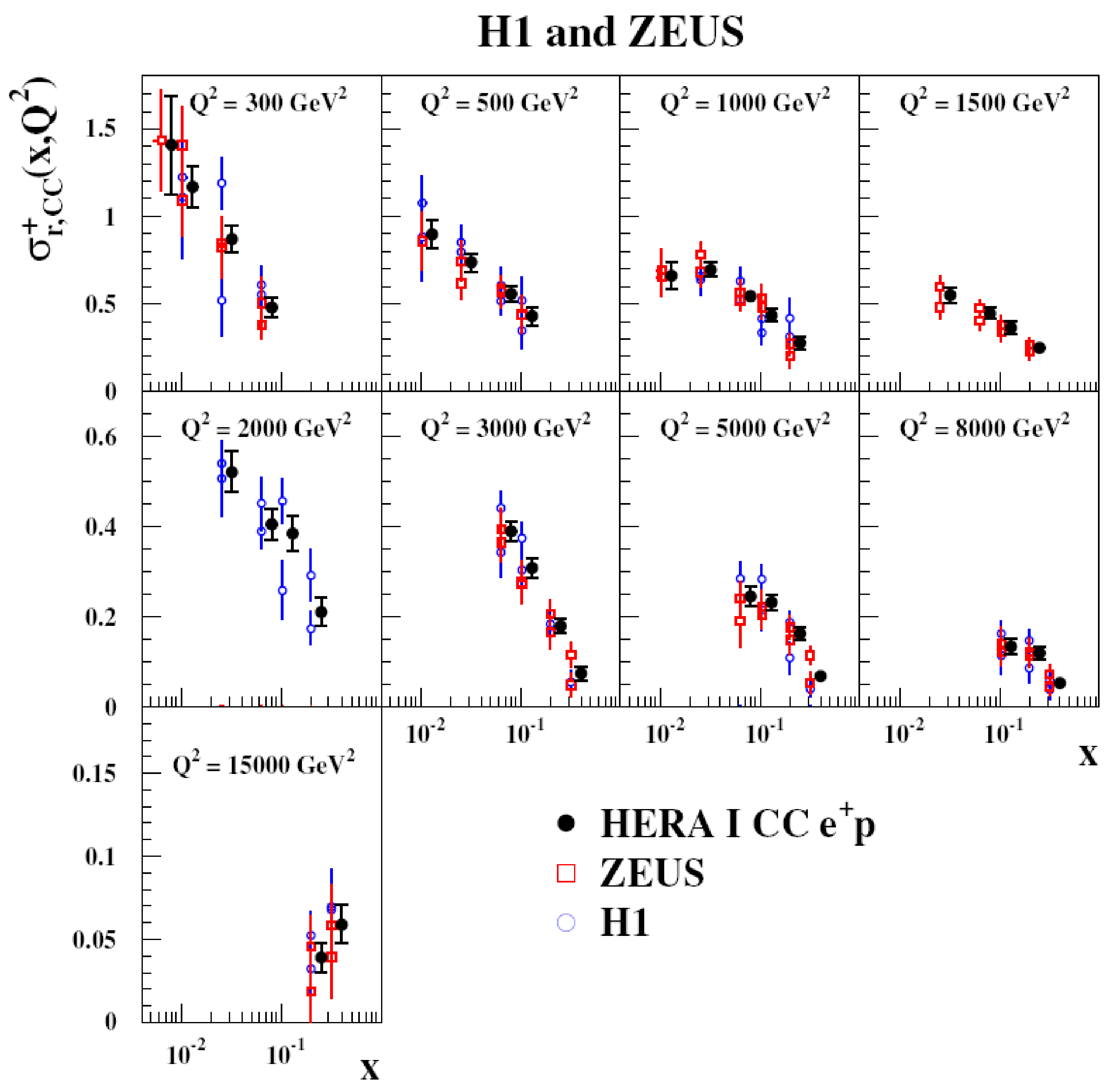
NC e+ [0.045,3.5)
RMS=1.08
a)
NC e+ [3.5,100)
RMS=1.00
b)
NC e+ [100,30000]
RMS=0.83
c)
NC e-
RMS=0.71
d)
CC e+
RMS=1.08
e)
CC e-
RMS=1.01
f)
Entries
p

Pulls on Sys

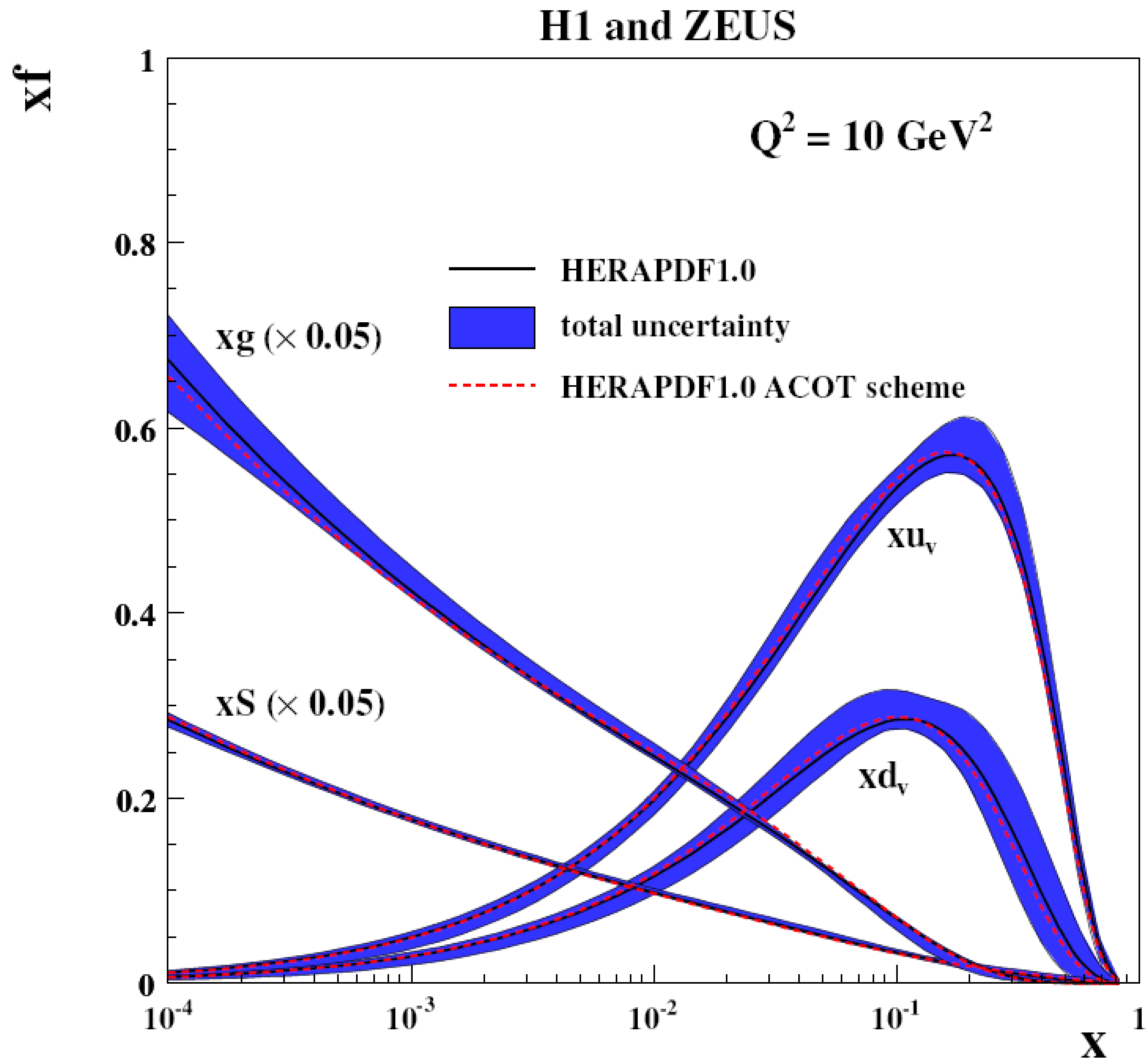




CC e+ Combination

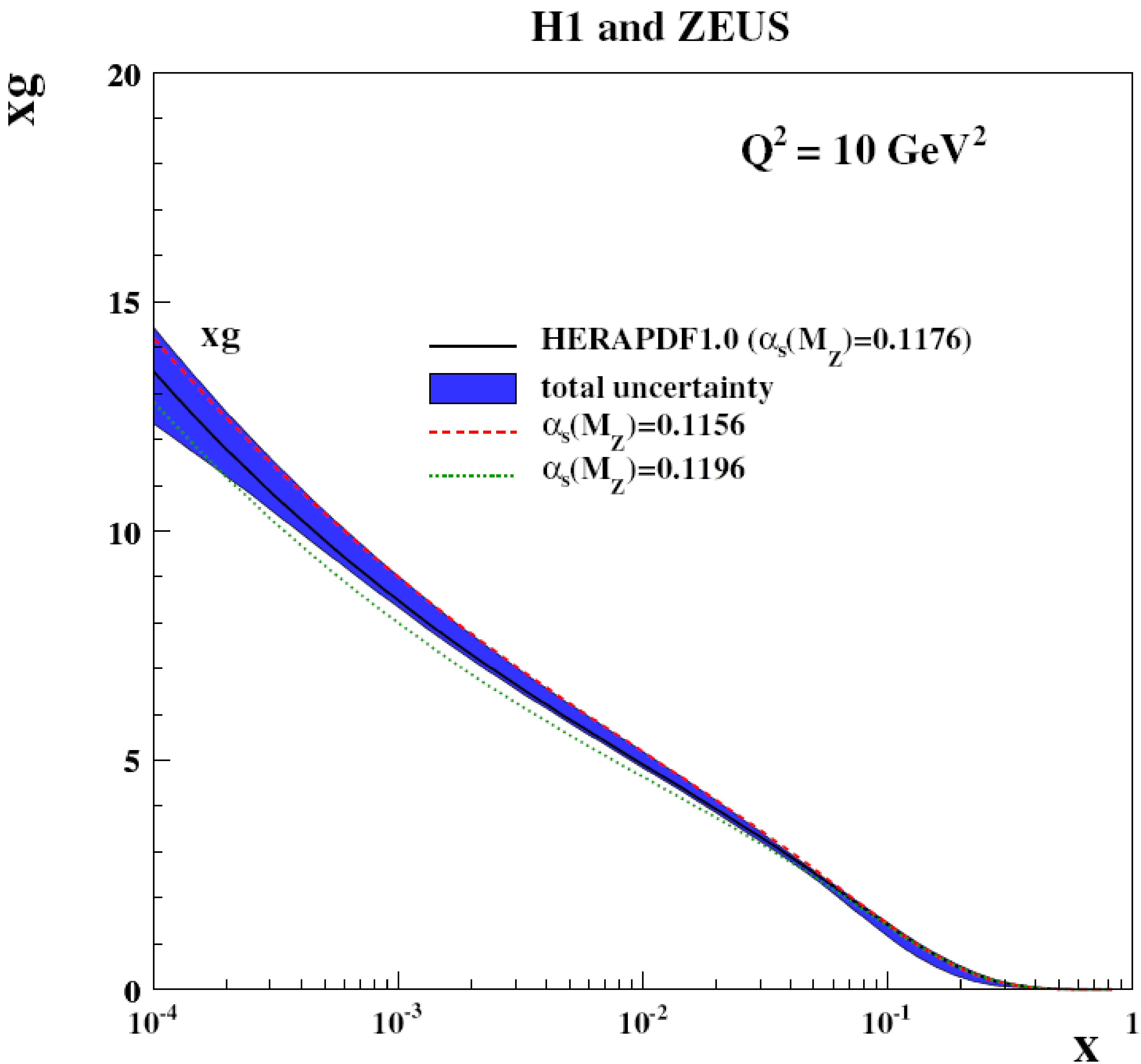


ACOT



H1 and ZEUS
xf
1
0.8
0.6
0.4
0.2
0
$Q^2 = 10\ GeV^2$
HERAPDF1.0
total uncertainty
HERAPDF1.0 ACOT scheme
xg (× 0.05)
xS (× 0.05)
xu_v
xd_v
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
x

Alpha_s



H1 and ZEUS
xg
20
15
10
5
0
$Q^2 = 10\ GeV^2$
xg
HERAPDF1.0 ($\alpha_s(M_Z)$=0.1176)
total uncertainty
$\alpha_s(M_Z)$=0.1156
$\alpha_s(M_Z)$=0.1196
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
X