Combined Measurements and PDF fits including HERA-II high Q^2 data

Voica A. Radescu

(Heidelberg Physikalisches Institut)

on behalf of H1 and ZEUS Collaboration

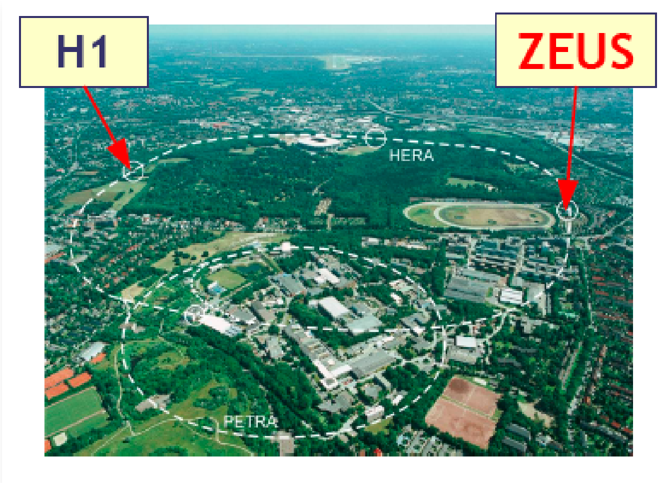
3rd of June, 2011

Outline

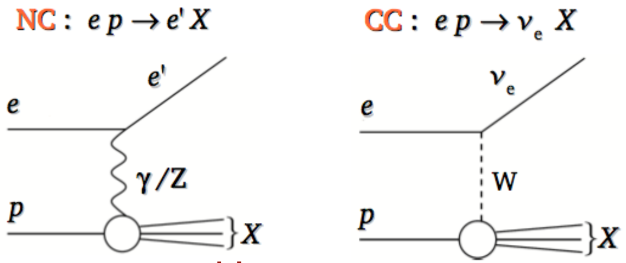
- HERA Experimental Settings
- H1 and ZEUS Data Combination
- HERA PDF analysis framework
- Results and Comparisons
- Summary

HERA at DESY

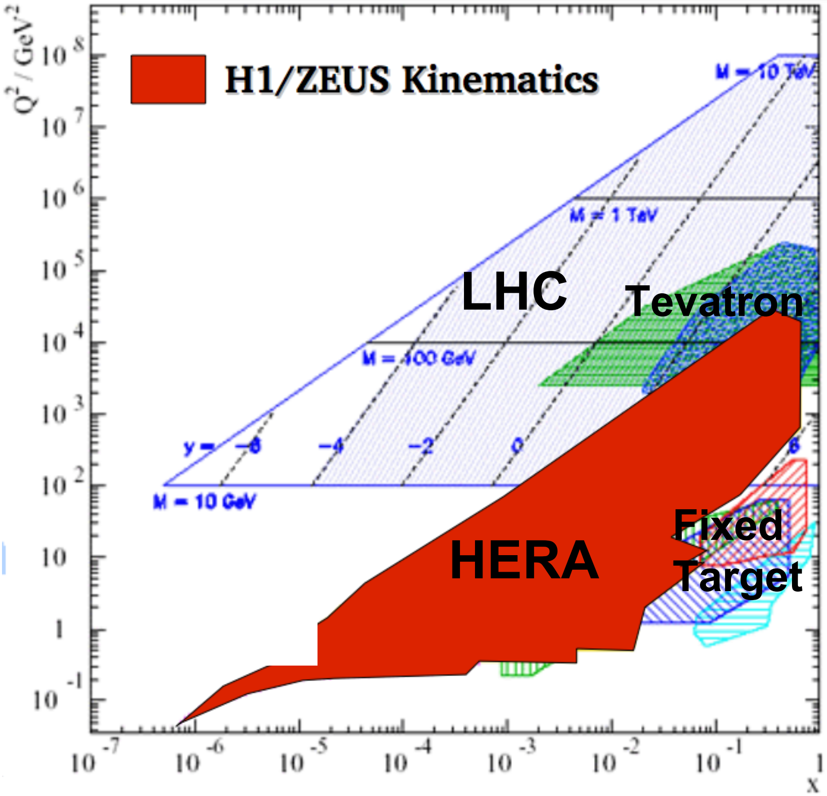
- HERA was world's only $e^{\pm}p$ collider
  - located at DESY, Hamburg - Germany
    - In operation for 15 years (1992-2007)
  - H1 and ZEUS collider experiments
    - General purpose detectors
    - ~1fb^{-1} of integrated luminosity of physics data.



- HERA provides unique opportunity to study the structure of proton via DIS processes:



- Kinematic variables:
  - Virtuality of exchanged boson: $Q^2 = -q^2 = -(k - k')^2$
  - Bjorken scaling variable: $x = \frac{Q^2}{2p \cdot q}$
  - Inelasticity: $y = \frac{p \cdot q}{p \cdot k}$
  - Invariant centre of masss: $s = (k + p)^2 = \frac{Q^2}{xy}$



HERA-I	1992-2000	Ep=820,920 GeV	L~110/pb per exp.
HERA-II	2003-2007	Ep=920, 460,575 GeV	L~500/pb per exp.

Deep Inelastic Scattering at HERA

Neutral Current:

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

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

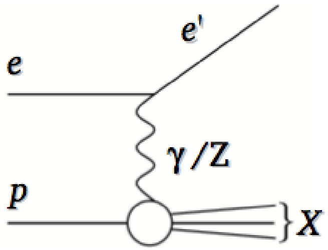
- xF_3 only sensitive at large Q^2 ($\sim M_Z^2$)
- F_L only sensitive at low Q^2 and high y
- F_2 dominates

$$xF_3 \sim \sum(xq_i - x\bar{q}_i)$$

$$F_L \sim \alpha_S g$$

$$F_2 \sim \sum e_i^2(xq_i + x\bar{q}_i)$$

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

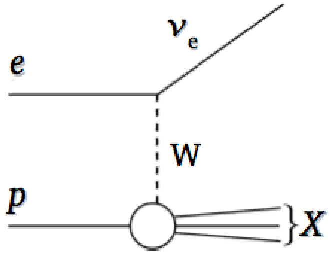


Charged Current: provides important flavour decomposition

e-p: $$\frac{d^2\sigma^-_{CC}}{dxdQ^2} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)\left[u + c + (1-y)^2(\bar{d} + \bar{s})\right]$$

e+p: $$\frac{d^2\sigma^+_{CC}}{dxdQ^2} = \frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)\left[\bar{u} + \bar{c} + (1-y)^2(d + s)\right]$$

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



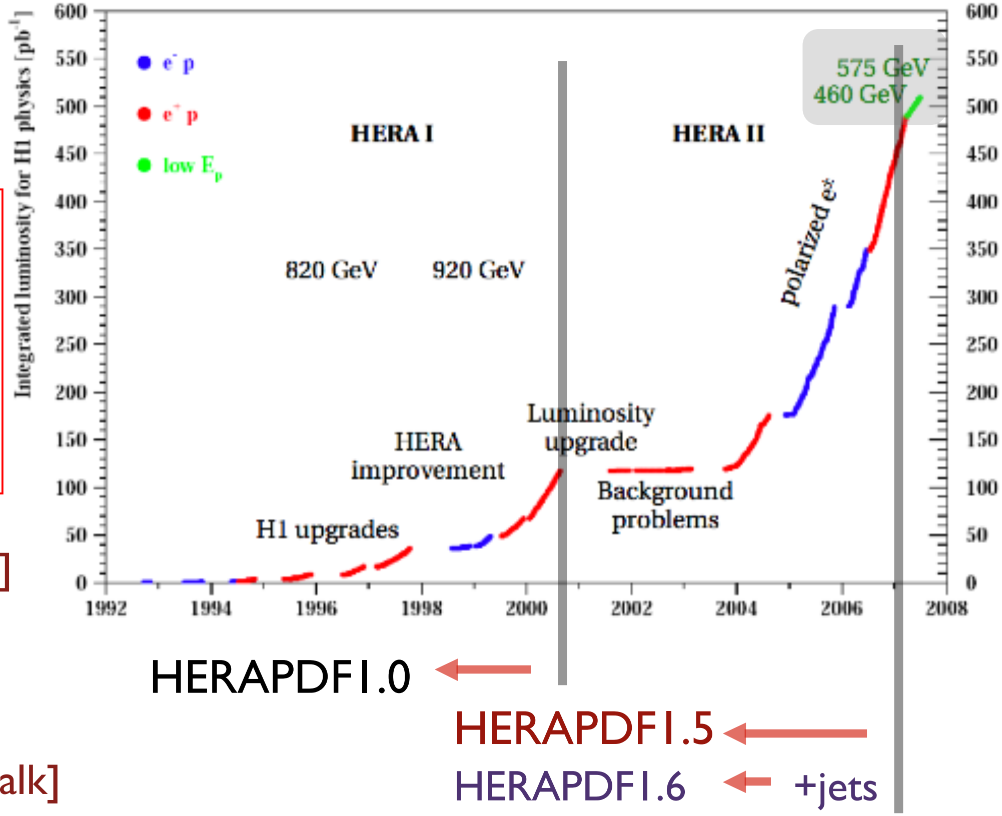
Input Data from HERA into the HERAPDF fits

- Combined HERA I inclusive data
  [JHEP01(2010) 109]
  - HERAPDF1.0 NLO (full errors) and NNLO
  - Data used in NNPDF2.0(1), CT10, ABKM

- Combined HERA I+high Q^2 HERA II Data [prelim]:
  - Accurate measurements in high Q^2 region
    - Sensitivity to valence quarks
  - HERAPDF1.5, HERAPDF1.5f (full errors)
    - NLO (full errors)
    - **NNLO (full errors)**

- H1 and ZEUS DIS Jet data [See A. Cooper's talk]
  - HERAPDF1.6 NLO (full errors)
  - **Determination of strong coupling**

- Combined Charm F_2 data [prelim] [See P. Roloff's talk]
  - Provides constraints on charm mass
  - Accounts for some differences among various PDF sets



- Low Energy Data HERA II [EPJ(2011)71]:
  [See A. Petrukhin's talk]
  - Accurate measurement in $Q^2 \geq 1.5$ GeV^2 range, sensitive to structure function F_L:
    - Investigate the low Q^2 region;
    - Test sensitivity to different heavy flavour treatments

Combination of the H1 and ZEUS Measurements

- Ultimate precision is obtained by combining the H1 and ZEUS measurements.
- The combination procedure is performed before QCD analysis:
  - Based on χ^2 minimisation procedure allowing systematic error sources free in the fit
    - ➢ Improvement on Statistical precision:
      - H1 and ZEUS collected similar amounts of physics data.
    - ➢ Improvement of Systematic precision:
      - H1 and ZEUS have different detectors and use different analysis techniques;
      - H1 and ZEUS have different sensitivities to similar sources of correlated systematic unc.

⇒ Combination of HERA I data was published in [JHEP01 (2010) 109] ⇒ HERAPDF1.0

- Preliminary High Q^2 HERA II data included in combination on top of HERA I data.

ZEUS CC e^-p	175 pb^{-1}	EPJ C 61 (2009) 223-235
ZEUS CC e^+p	132 pb^{-1}	EPJ C 70 (2010) 945-963
ZEUS NC e^-p	170 pb^{-1}	EPJ C 62 (2009) 625-658
H1 CC e^-p	149 pb^{-1}	H1prelim-09-043
H1 CC e^+p	180 pb^{-1}	H1prelim-09-043
H1 NC e^-p	149 pb^{-1}	H1prelim-09-042
H1 NC e^+p	180 pb^{-1}	H1prelim-09-042

- χ^2/dof=967/1032
- 131 systematic uncertainties and 3 additional procedural

⇒ HERAPDF1.5

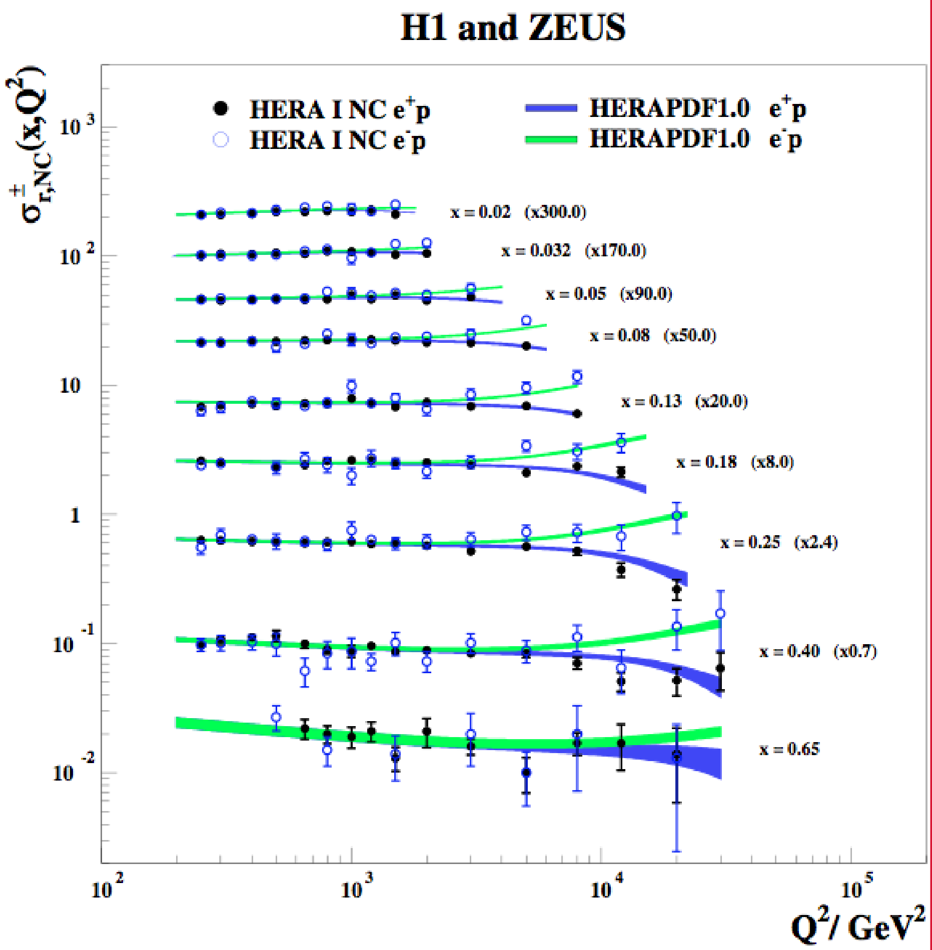
ZEUS NC e^+p	135 pb^{-1}	ZEUS-prel-11-003

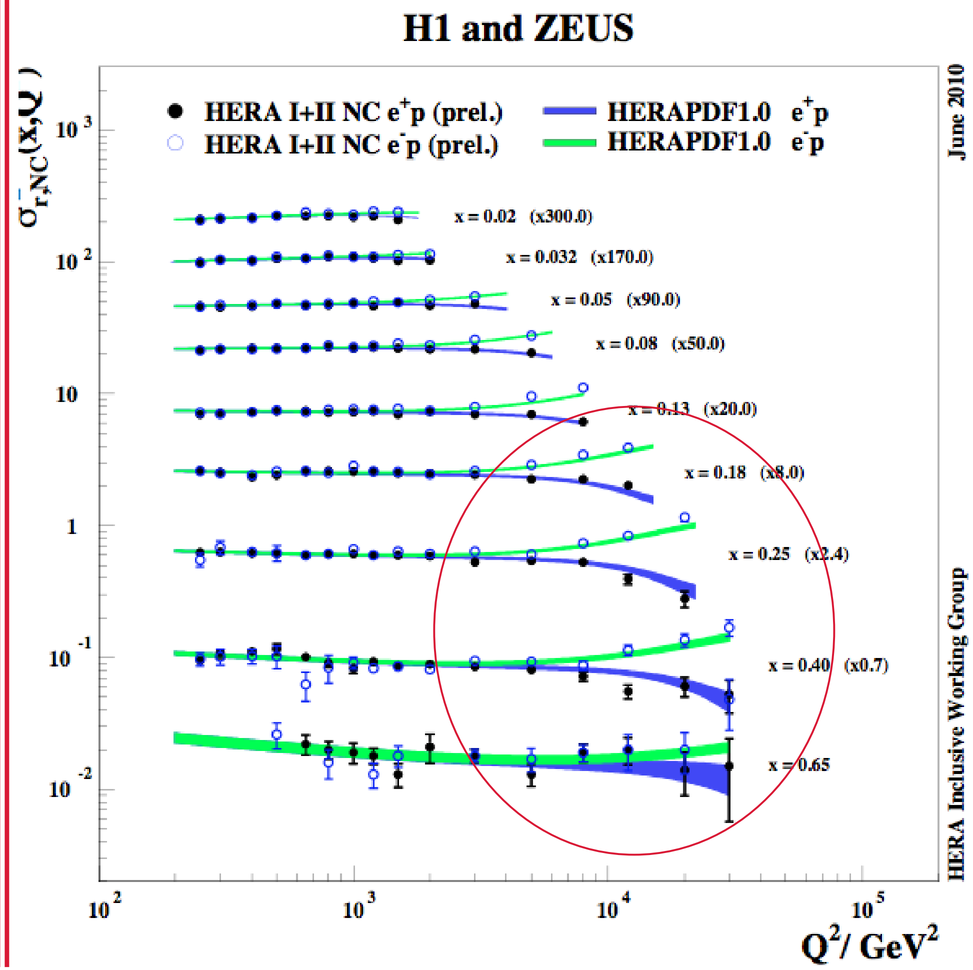
To be included
In final Combination

High Q^2 NC Cross Sections

At High Q^2 ⇒interference term $Z\gamma$: destructive(e^+p) and constructive (e^-p)

HERA I → HERA I+II

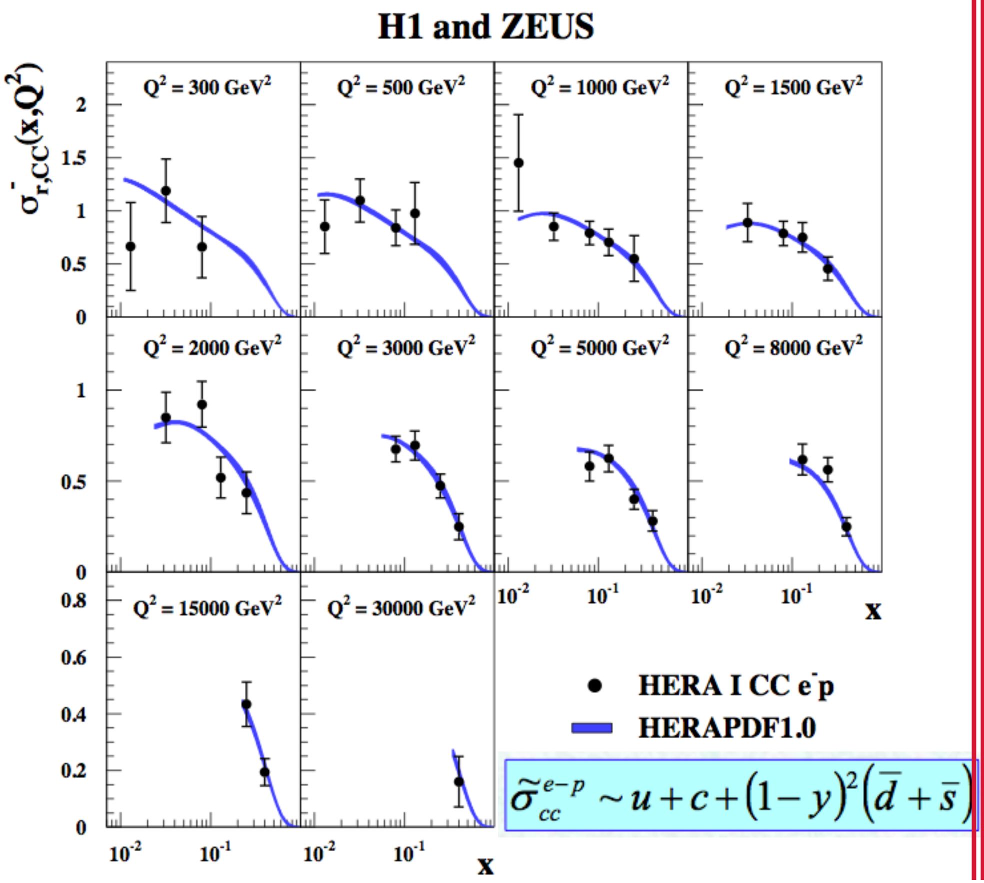




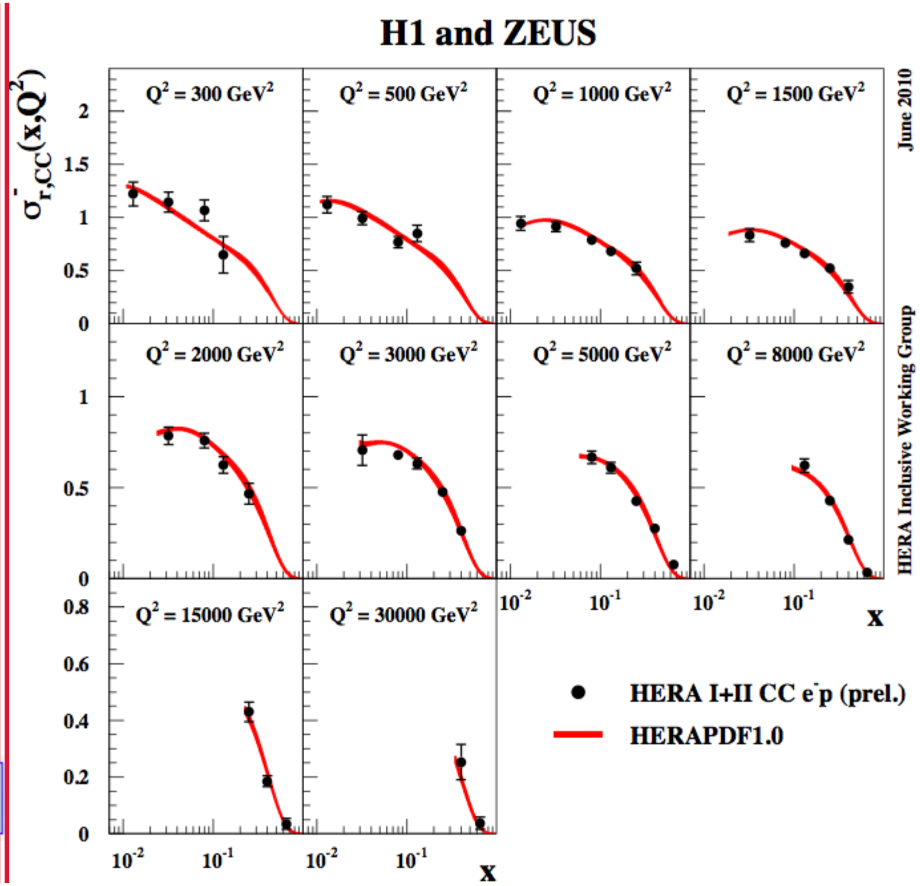
Larger HERA II luminosity yields in significant improvement in precision at high x, Q^2

High Q^2 CC Cross Sections

HERA I → HERA I+II



$$\tilde{\sigma}_{cc}^{e-p} \sim u + c + (1-y)^2 (\bar{d} + \bar{s})$$

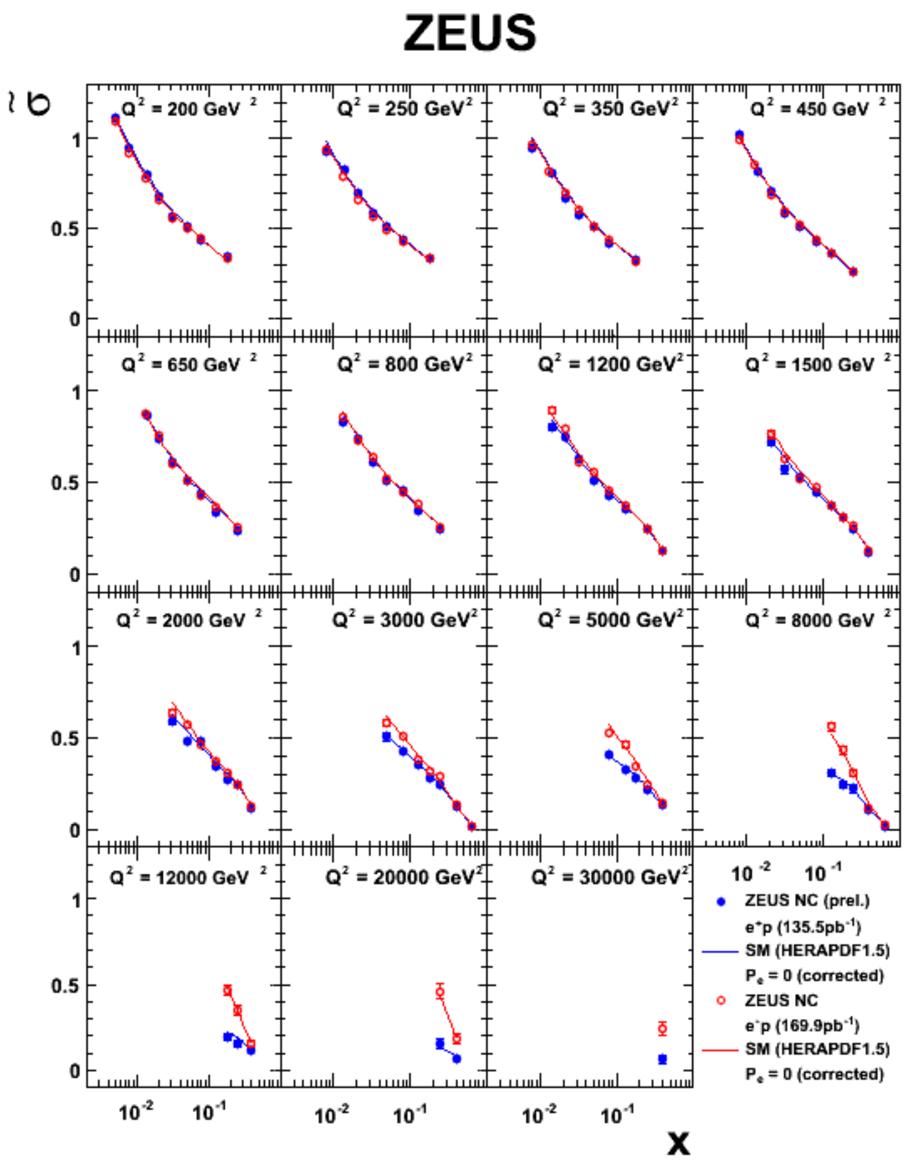


Much more precise CC measurements after including new high Q^2 HERA II set!

New High Q^2 NC Data

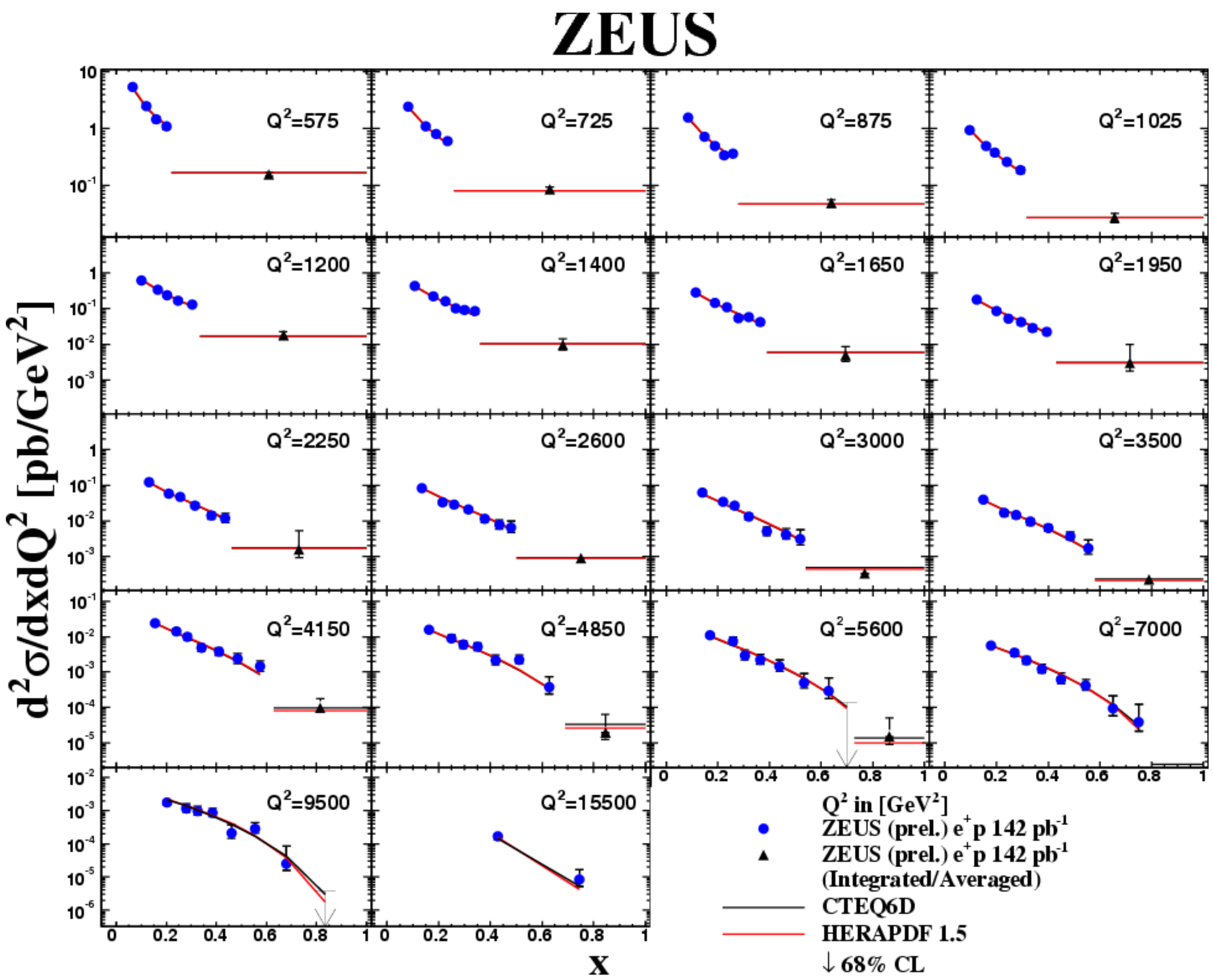
- New preliminary ZEUS e^+p NC data at High Q^2 is available:
  - Will provide additional constrain for PDFs at high x

- To be included in Final HERA Combination and future fits



New High x NC Data

- New NC measurement at high x from ZEUS:
  - x reconstruction relies on jets
  - Force jets to balance pT of electron
  - Gives better x resolution
- To be included in Final HERA Combination and future fits



QCD Fit Settings for HERAPDFs

PDF determination at HERA

- HERA PDFs are determined from QCD Fits to solely HERA data of Q^2>3.5 GeV^2
- The QCD settings are optimised for HERA measurements of proton structure functions (dominated by gamma exchange)

$$F_2(x,Q^2) = \frac{4}{9}(xU + x\overline{U}) + \frac{1}{9}(xD + x\overline{D})$$

  - NLO (and NNLO) DGLAP evolution equations, RT-VFNS (as for MSTW08)
  - PDF parametrised at the starting scale Q_0^2: $xg, xu_{val}, xd_{val}, x\bar{U} = x\bar{u}(+x\bar{c}), x\bar{D} = x\bar{d} + x\bar{s}(+x\bar{b})$
    Q_0^2 = 1.9 GeV^2 (below m_c)
    - central fit with 10 free parameters (standard) - for HERAPDF1.0 (NLO and NNLO), HERAPDF1.5(NLO)

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

    - extended fit with 14 free parameters (flexible) - for HERAPDF1.5f (NLO), HERAPDF1.5 (NNLO) and for jet fits HERAPDF1.6 [see A. Cooper's talk]

$$xf(x,Q_0^2) = Ax^B(1-x)^C(1+Dx+Ex^2) - A'x^{B'}(1-x)^{25}$$

Imposing momentum sum rules:

$$\int_0^1 dx \cdot (xu_v + xd_v + x\bar{U} + x\bar{D} + xg) = 1$$

$$\int_0^1 dx \cdot u_v = 2 \qquad \int_0^1 dx \cdot d_v = 1$$

Additional Constraints:

$x\bar{s} = f_s x\bar{D}$ strange sea is a fixed fraction f_s of $\bar{D}$ at Q_0^2

$B_{Ubar} = B_{Dbar}$
sea = 2 x (Ubar +Dbar)
Ubar = Dbar at x=0

In 10p fit: Buv=Bdv

Sources of PDF uncertainties at HERA

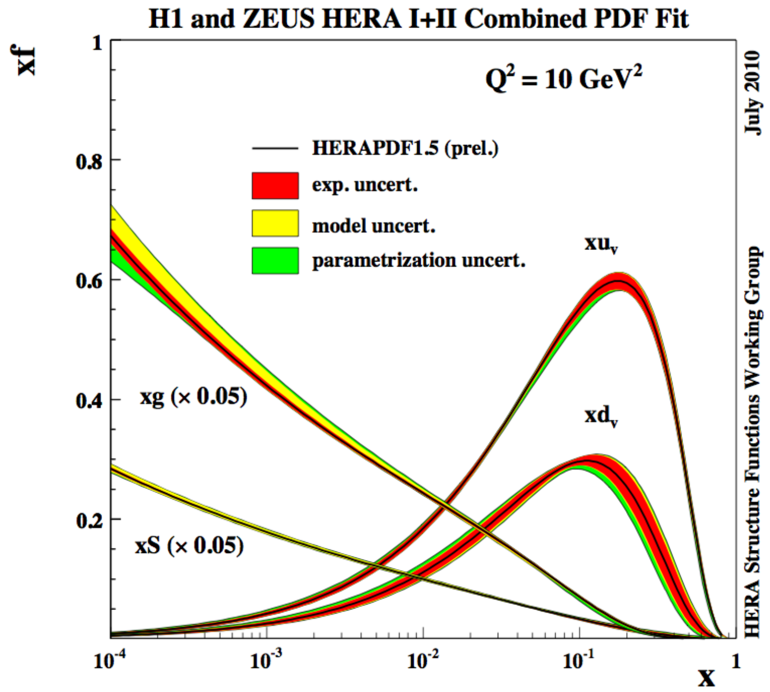
- **Experimental Uncertainties:**
  - Consistent data sets → use $\Delta\chi^2 = 1$
  - Cross checked with Monte Carlo method [PDF4LHC Interim Report arXiv:1101:0536]

- **Model Uncertainties:**
  - following variations have been considered

Variation	Standard Value	Lower Limit	Upper Limit
f_s	0.31	0.23	0.38
m_c [GeV]	1.4	$1.35^{(a)}$	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	$1.5^{(b)}$	$2.5^{(c,d)}$

$^{(a)} Q^2_0 = 1.8$ $^{(c)} m_c = 1.6$

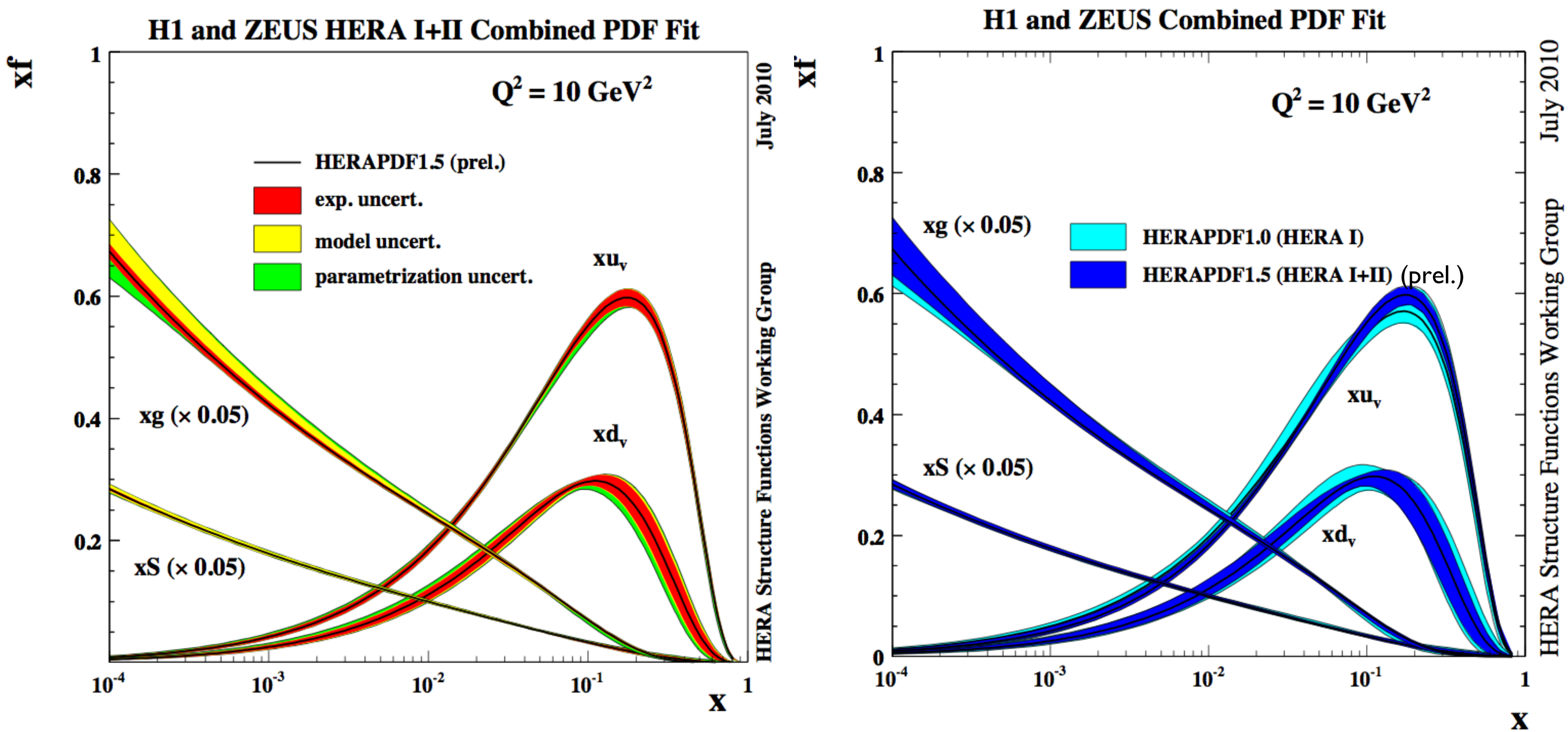
$^{(b)} f_s = 0.29$ $^{(d)} f_s = 0.34$



- **Parametrisation Uncertainties:**
  - An envelope formed from PDF fits using other variants of parametrisation form at the starting scale (especially sensitive to the higher x region):
    - Scanning of parameter space
    - Q_0^2 variation and a more flexible gluon parametrisation

Results based on HERA I+II data: HERAPDF1.5 (NLO)

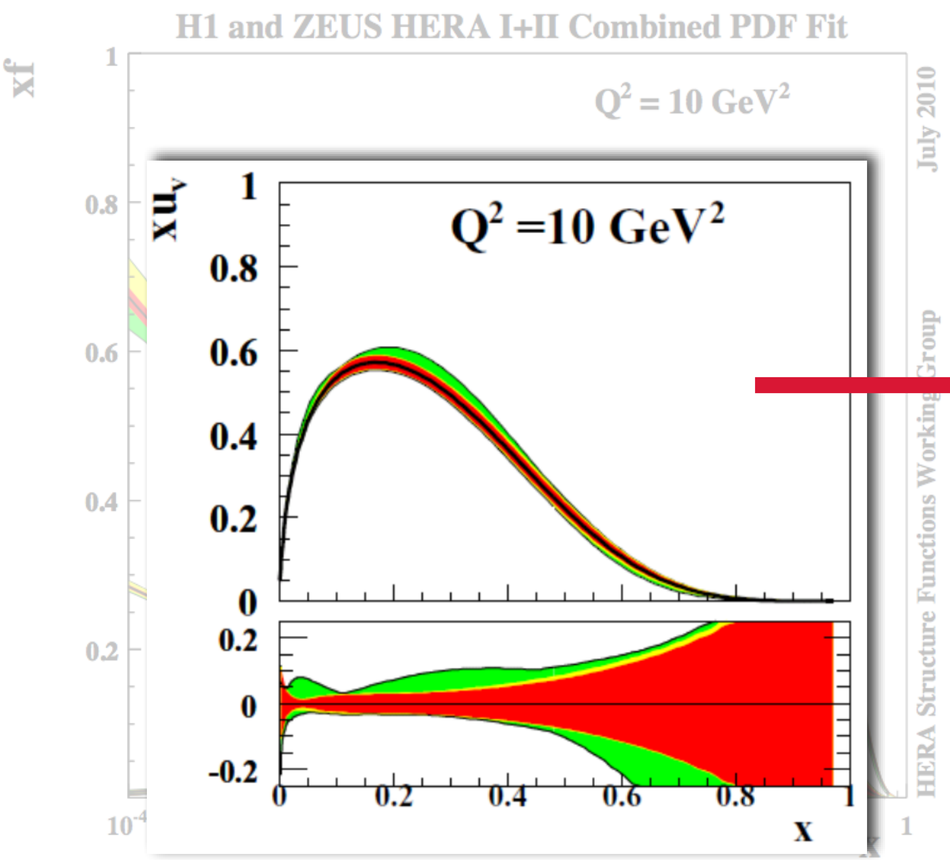
- xg, xu_v, xd_v, xS ($xS=x\bar{U}+x\bar{D}$) at the scale $Q^2=10$ GeV^2



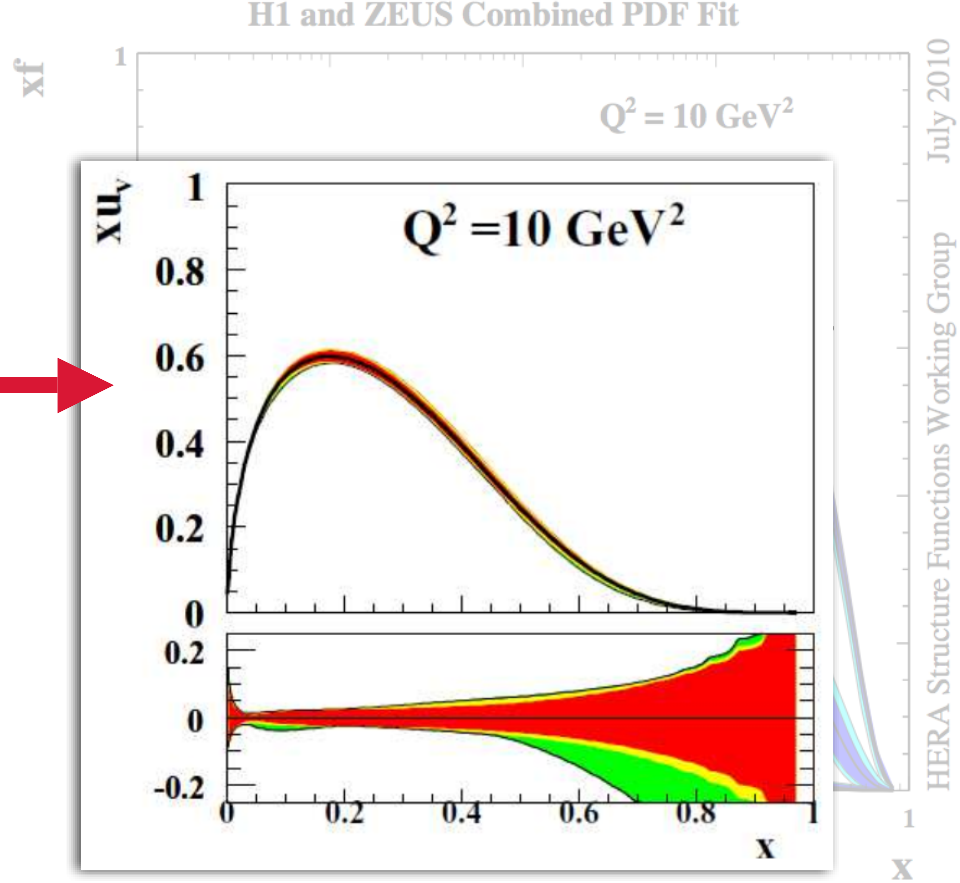
- Inclusion of the HERA II data reduces the uncertainties on PDFs in the high x region especially visible on the valence distributions!
    - See HERAPDF1.5(prel) vs HERAPDF1.0

Results based on HERA I+II data: HERAPDF1.5 (NLO)

HERA I



HERA I+ II



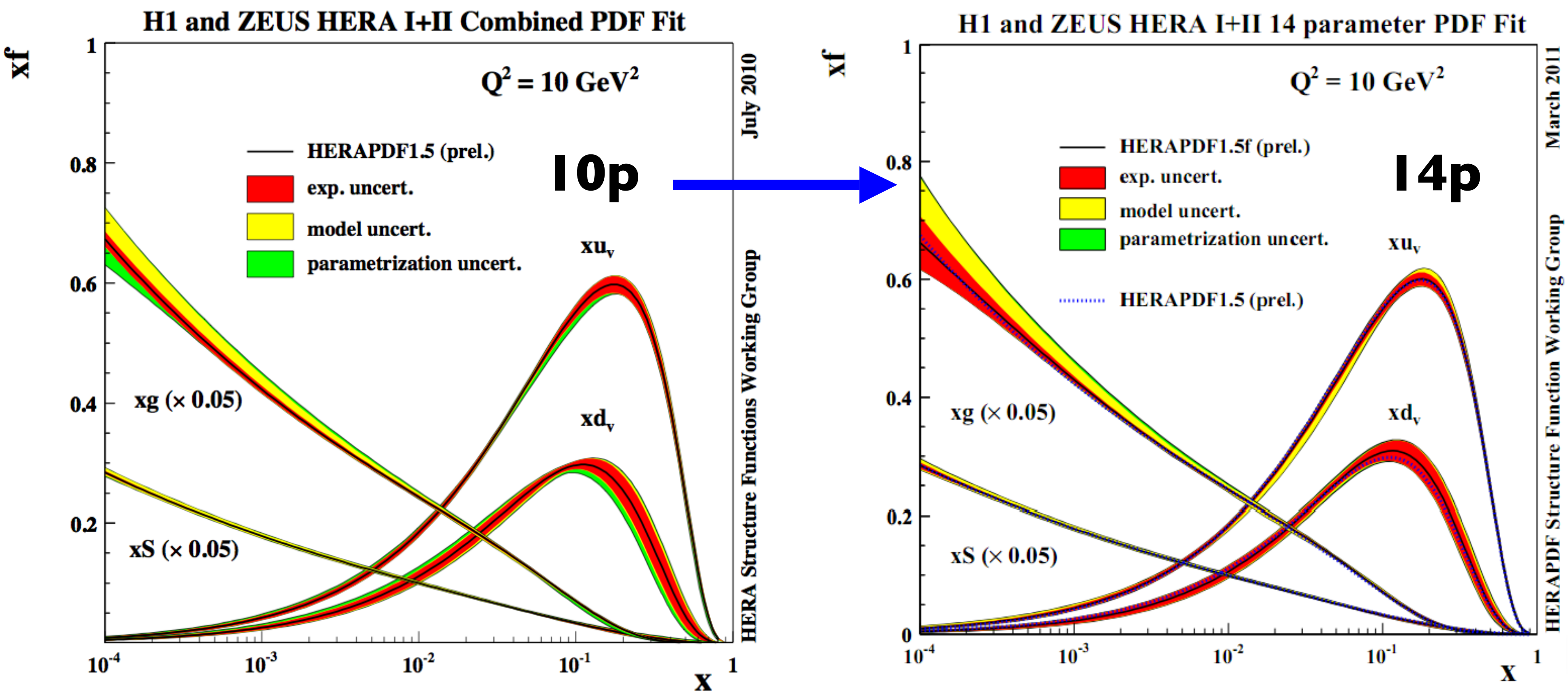
- Inclusion of the HERA II data reduces the uncertainties on PDFs in the high x region especially visible on the valence distributions!
  - See HERAPDF1.5(prel) vs HERAPDF1.0

HERAPDF1.5 vs HERAPDF1.5f at NLO

- Additional studies show that a more flexible gluon parametrisation would be more suitable for further studies (NNLO fits, addition of the jet data):

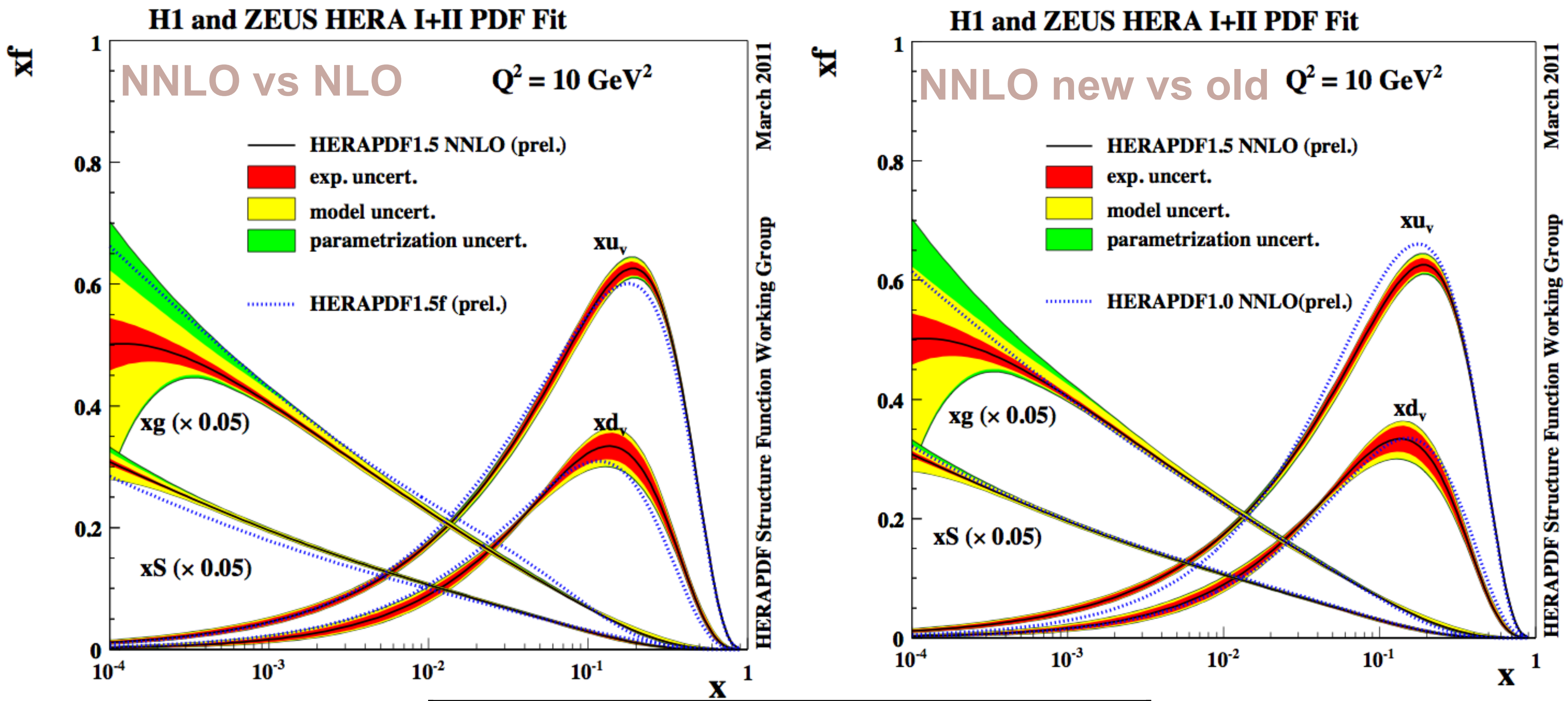
$$xg(x,Q_0^2) = A \cdot x^B \cdot (1-x)^C - A' \cdot x^{B'} \cdot (1-x)^{25}$$

- HERA II data can provide constraints for valence distributions, hence the assumption of Buv=Bdv is released and a more flexible valence parametrisation can be used.



Results based on HERA I+II data: HERAPDF1.5 (NNLO)

- Fits performed to HERA I data (as used for HERAPDF1.0) at NNLO using RT-VFNS:
  α_S(Mz) at NNLO = 0.1176



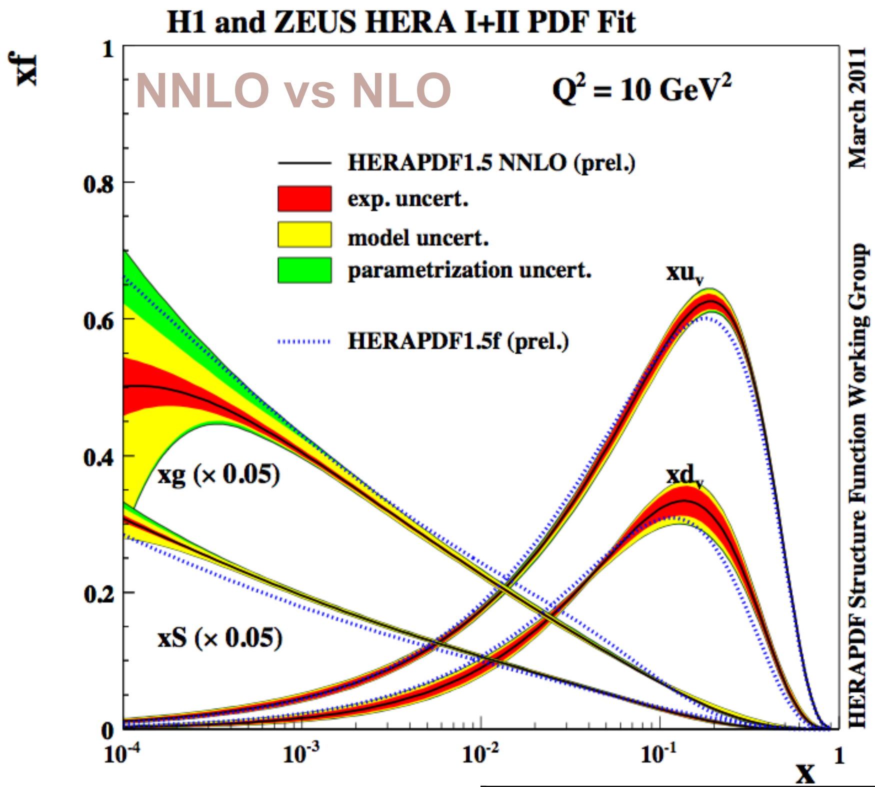
scheme	NNLO α_S(Mz)=0.1176	NLO α_S(Mz)=0.1176
All χ^2/dof	744.3/660	735.1/660

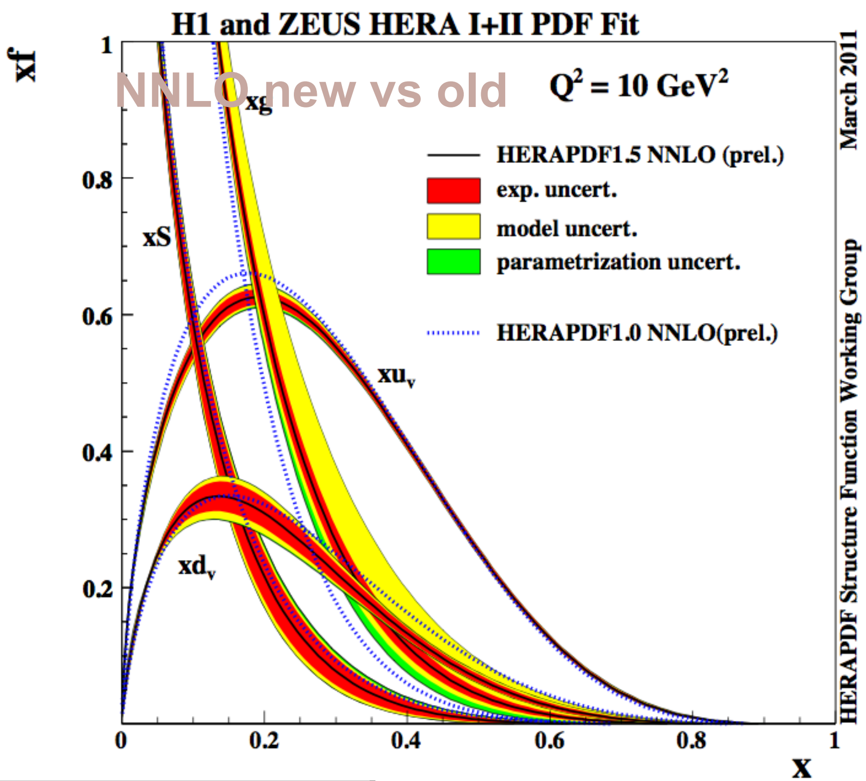
- HERAPDF1.5 NLO vs NNLO is in much better agreement than for HERAPDF1.0 case
  - use of a more flexible parametrisation for the central fit (10 parameters vs 14 parameters fit)
- HERAPDF1.5 NNLO vs HERAPDF1.0 NNLO yields a harder gluon and softer valence at high x

Premiere!

Results based on HERA I+II data: HERAPDF1.5 (NNLO)

- Fits performed to HERA I data (as used for HERAPDF1.0) at NNLO using RT-VFNS:
  $\alpha_S(Mz)$ at NNLO = 0.1176

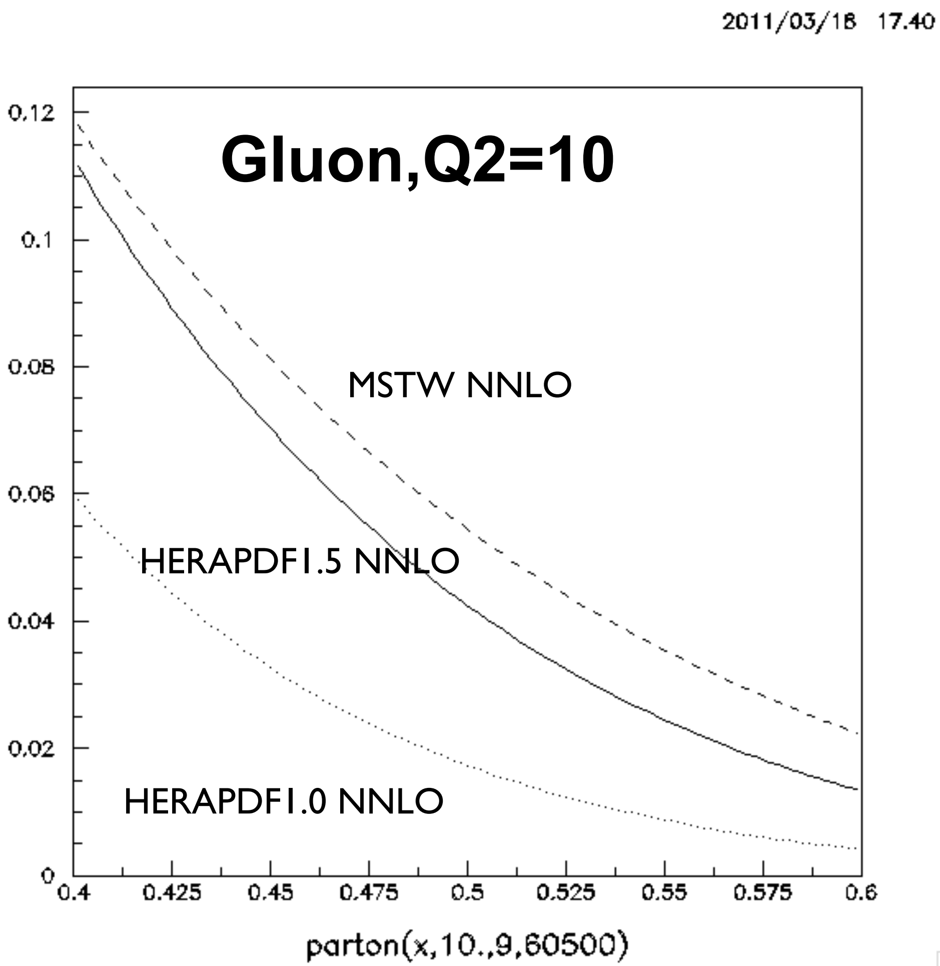


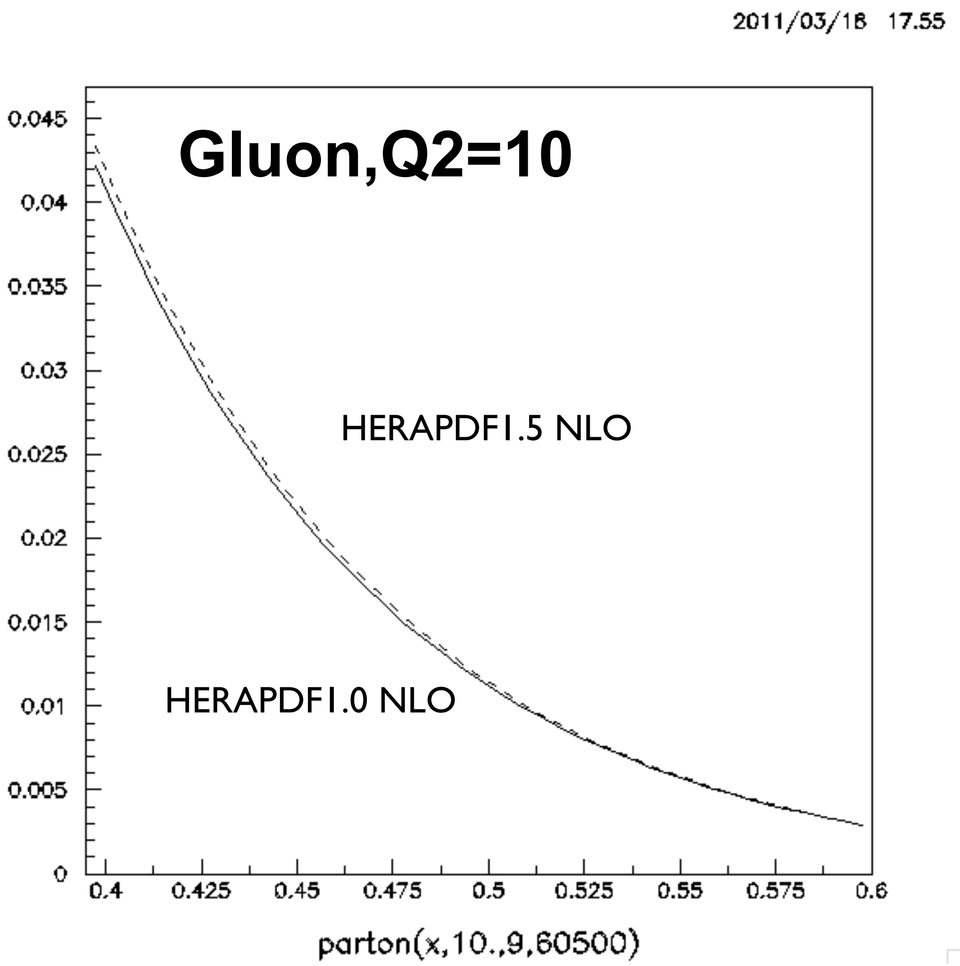


scheme	NNLO $\alpha_S(Mz)$=0.1176	NLO $\alpha_S(Mz)$=0.1176
All χ^2/dof	744.3/660	735.1/660

- HERAPDF1.5 NLO vs NNLO is in much better agreement than for HERAPDF1.0 case
  - use of a more flexible parametrisation for the central fit (10 parameters vs 14 parameters fit)
- HERAPDF1.5 NNLO vs HERAPDF1.0 NNLO yields a harder gluon and softer valence at high x

HERAPDF comparisons vs MSTW08



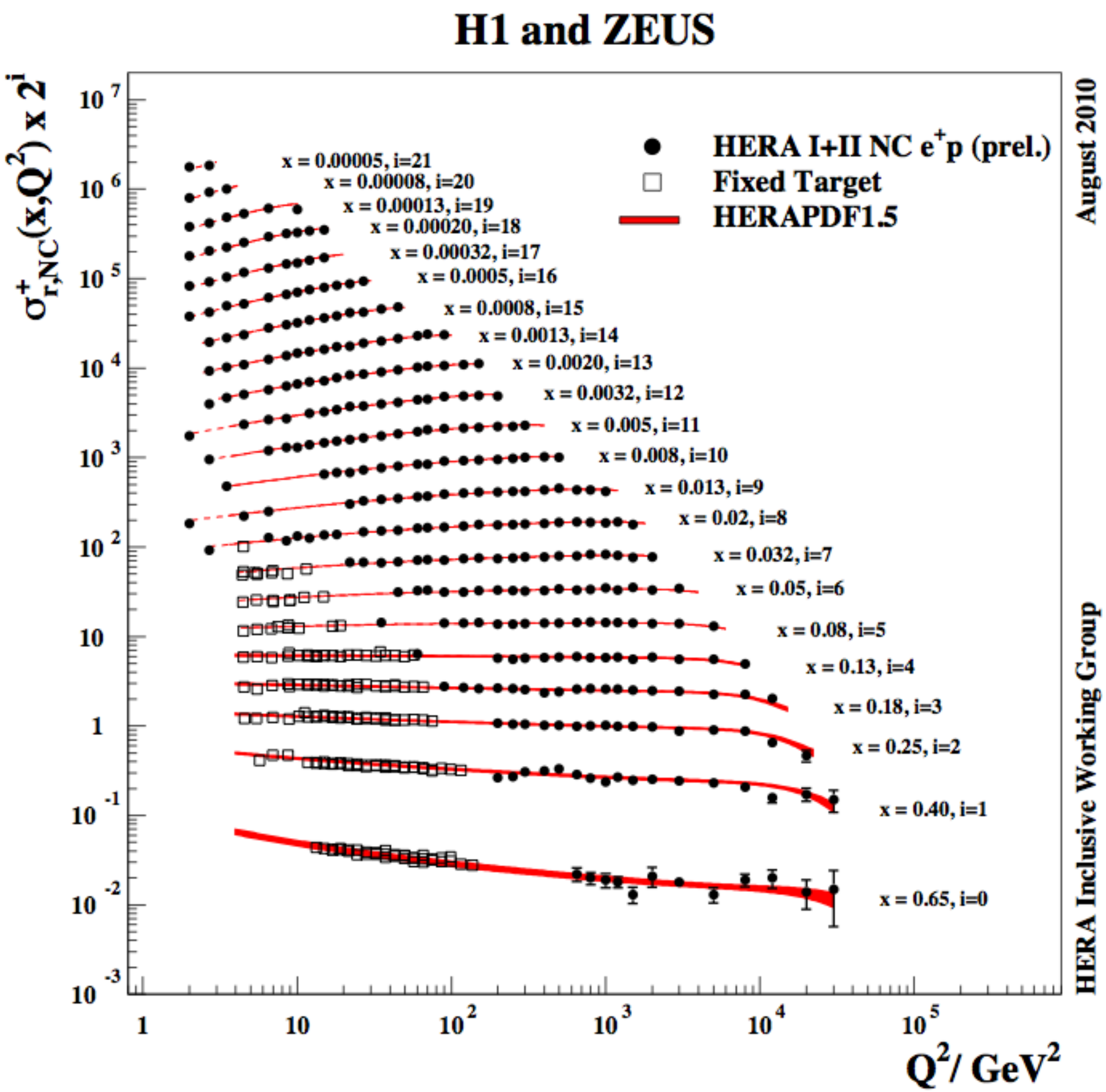


- HERAPDF1.0 NLO vs HERAPDF1.5NLO differences are minimal for gluon at high x
- HERAPDF1.0 NNLO vs HERAPDF1.5 NNLO large differences.

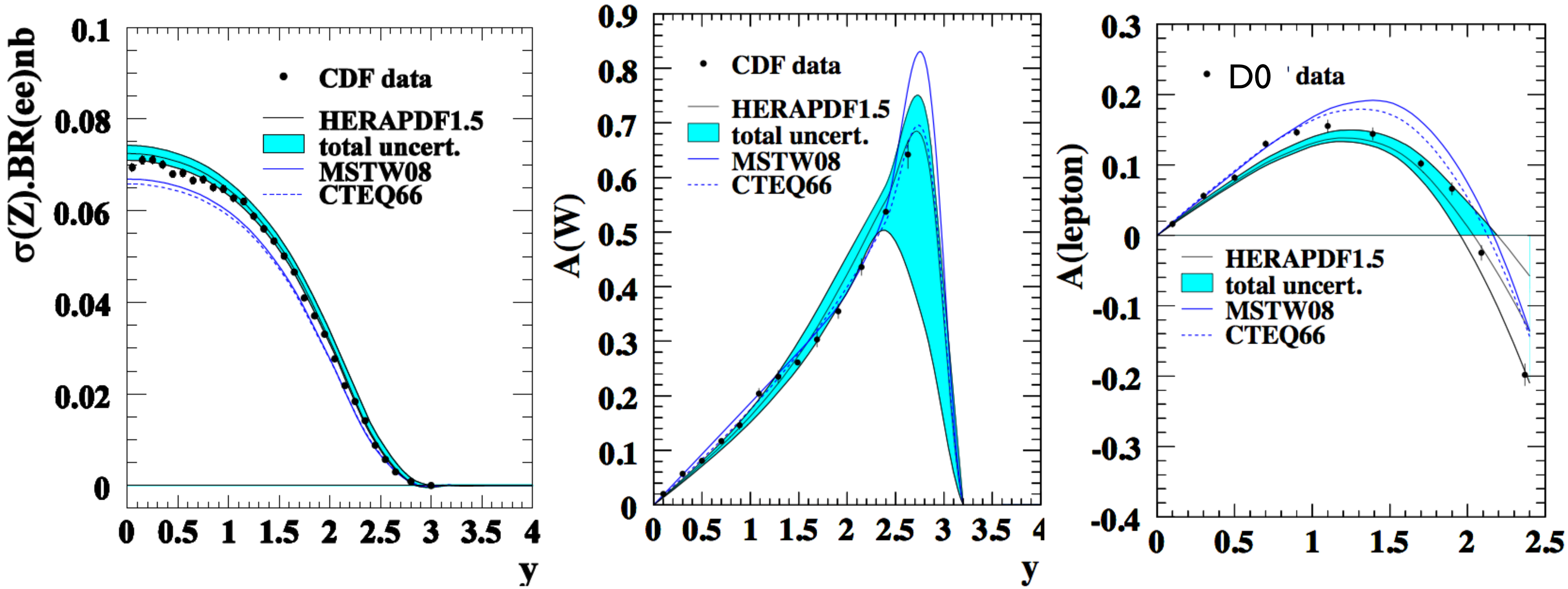
Predictions based on HERAPDFs

HERAPDF1.5 vs DIS Data

- Extended kinematic range of the HERA I and II data as compared to the fixed target data:
  - Fit line includes total error
- HERAPDF1.5 fit describes our data well over
- Extrapolation of the HERAPDF1.5 fits agree well with fixed target data:
  - SLAC and BCDMS



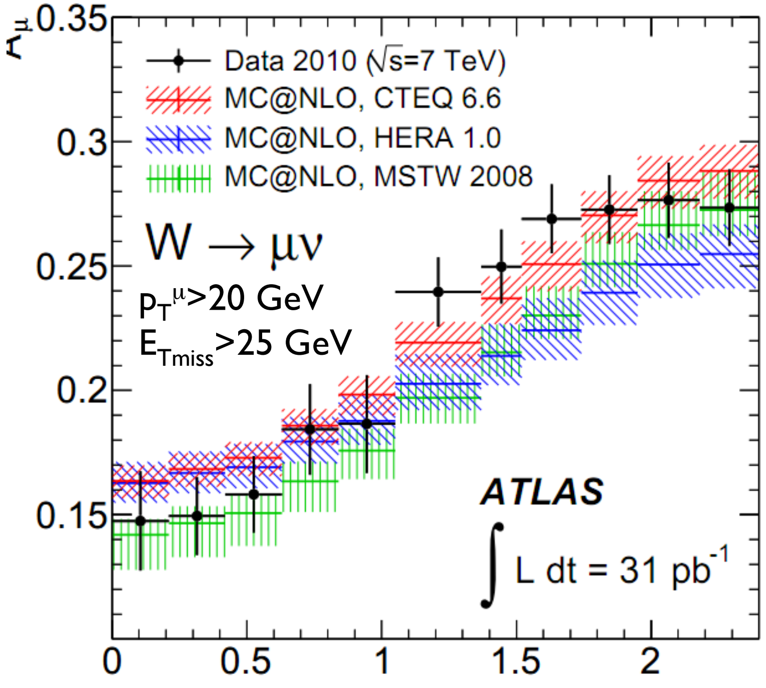
HERAPDF1.5 (NLO) vs Tevatron Data



- HERAPDF1.5 results in a reasonable agreement with the CDF data for Z rapidity, the W asymmetry and the D0 lepton asymmetry, even if this data is not included in the HERA fits.

- DIS data from HERA predicts well Z and W at Tevatron from the ppbar processes.

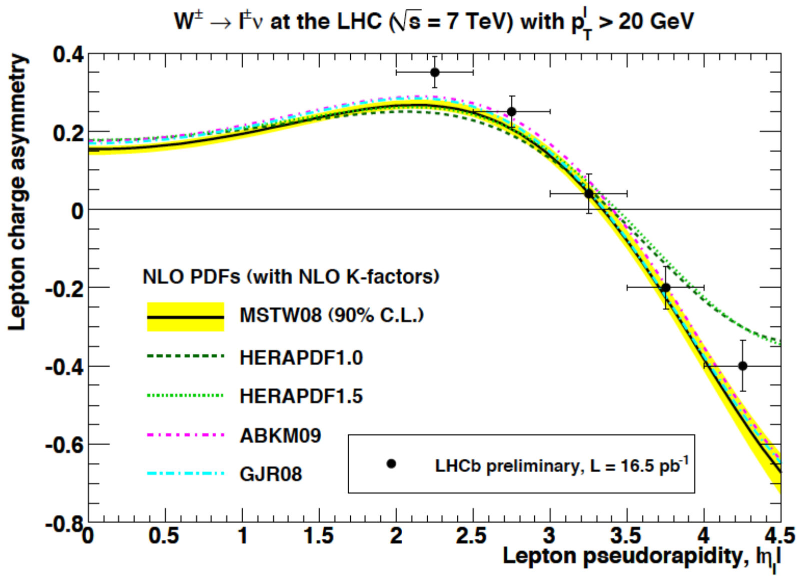
HERAPDF Predictions for W and lepton asymmetries at LHC

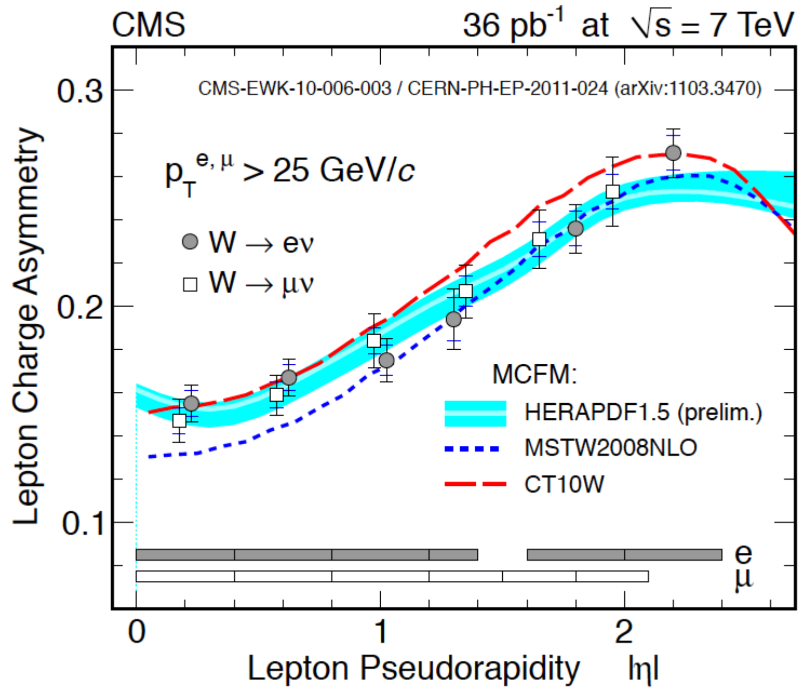


- W asymmetry is sensitive to differences between u and d
- Difference in u and d quarks can be better measured by all experiments at the LHC

$$A_{\pm}(y_W) = \frac{d\sigma/dy_W(W^+) - d\sigma/dy_W(W^-)}{d\sigma/dy_W(W^+) + d\sigma/dy_W(W^-)}$$

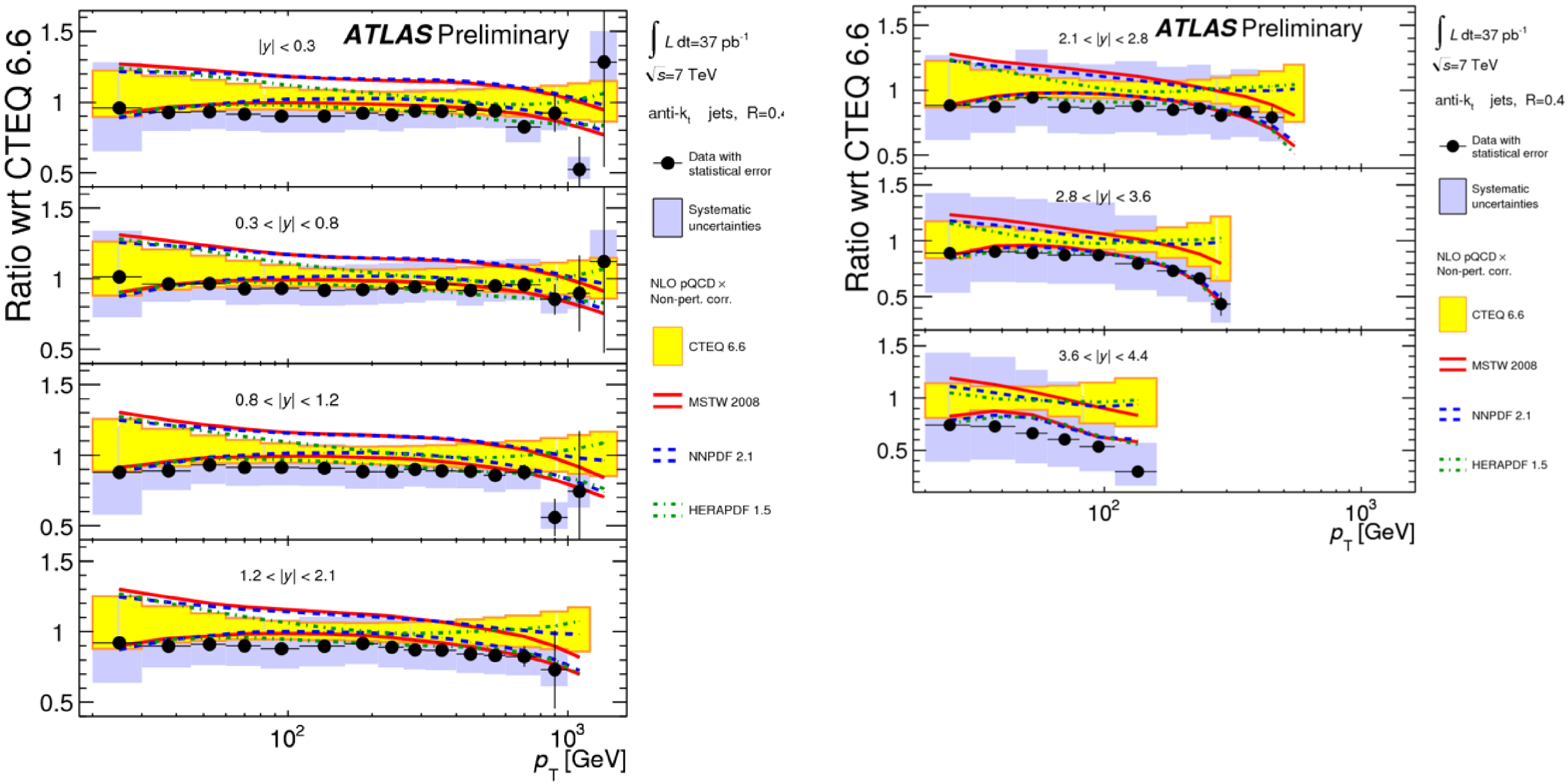
$$\approx \frac{u(x_1)\bar{d}(x_2) - d(x_1)\bar{u}(x_2)}{u(x_1)\bar{d}(x_2) + d(x_1)\bar{u}(x_2)} \approx \frac{u(x_1) - d(x_1)}{u(x_1) + d(x_1)}$$





HERAPDF provides good description to pp process too

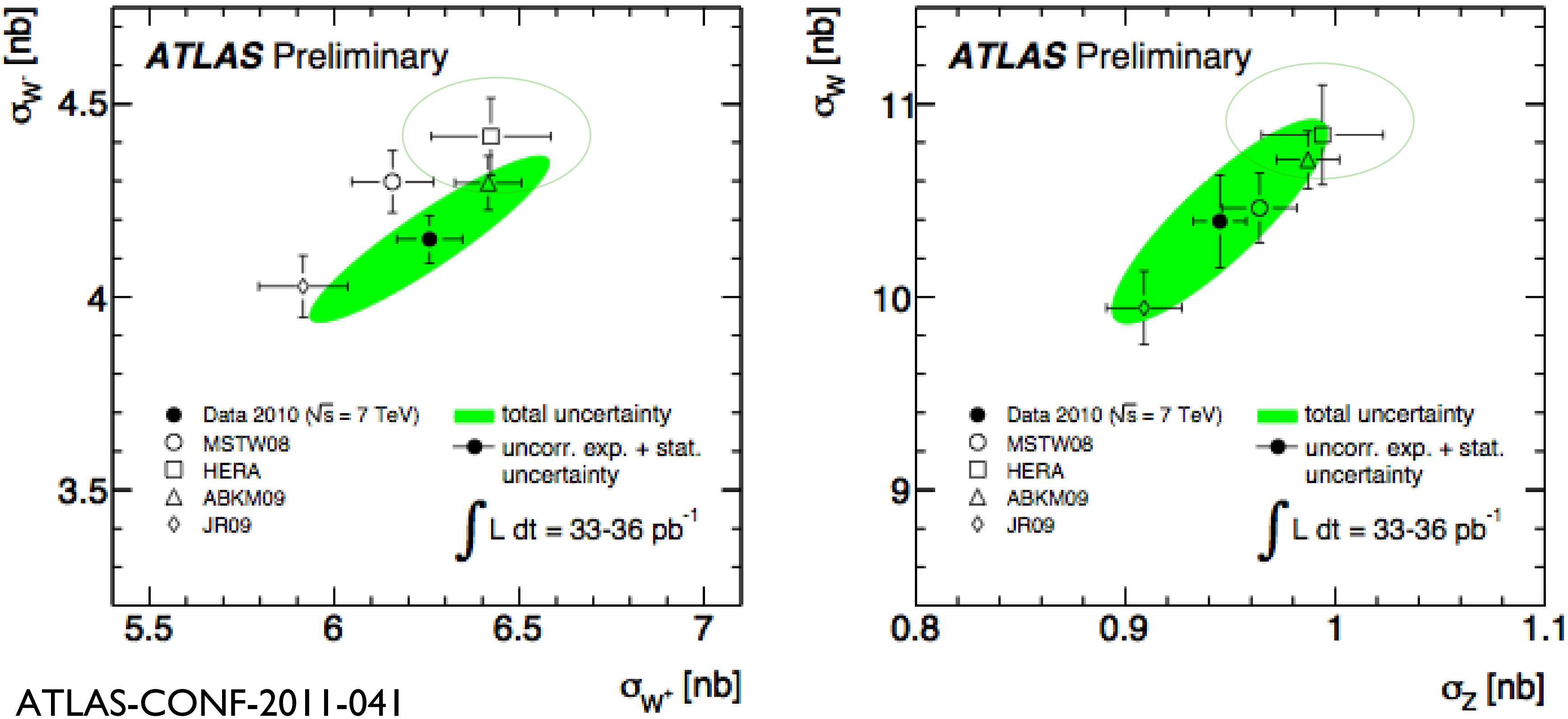
Predictions for ATLAS Jet Data



- New ATLAS measurement based on complete 2010 data set extending to forward and lower pT regions, with improved JES uncertainty.
- Best agreement seems to be with HERAPDF1.5, however experimental/theoretical uncertainties are sizeable

LHC predictions for W, Z cross sections

- Compare measured and predicted cross sections (NNLO):
  - HERAPDF1.0(alphas=0.1145), ABKM, JR09, MSTW08



ATLAS-CONF-2011-041

HERAPDF1.0 based solely on ep data provides a competitive prediction to the LHC data!

Summary

- HERA provides unique determinations of the proton structure and can predict related Standard Model processes.

- New preliminary combined HERA-II measurements improves accuracy at high x and allow for releasing of PDF assumptions:

  ➔ HERAPDF1.5 at NLO and NNLO with full error band

  - New measurements available with potential to further constrain the PDFs at high x to be included in the next data combination towards final HERAPDF release.

- HERAPDF predicts measurements from Fixed Target and Tevatron experiments well.

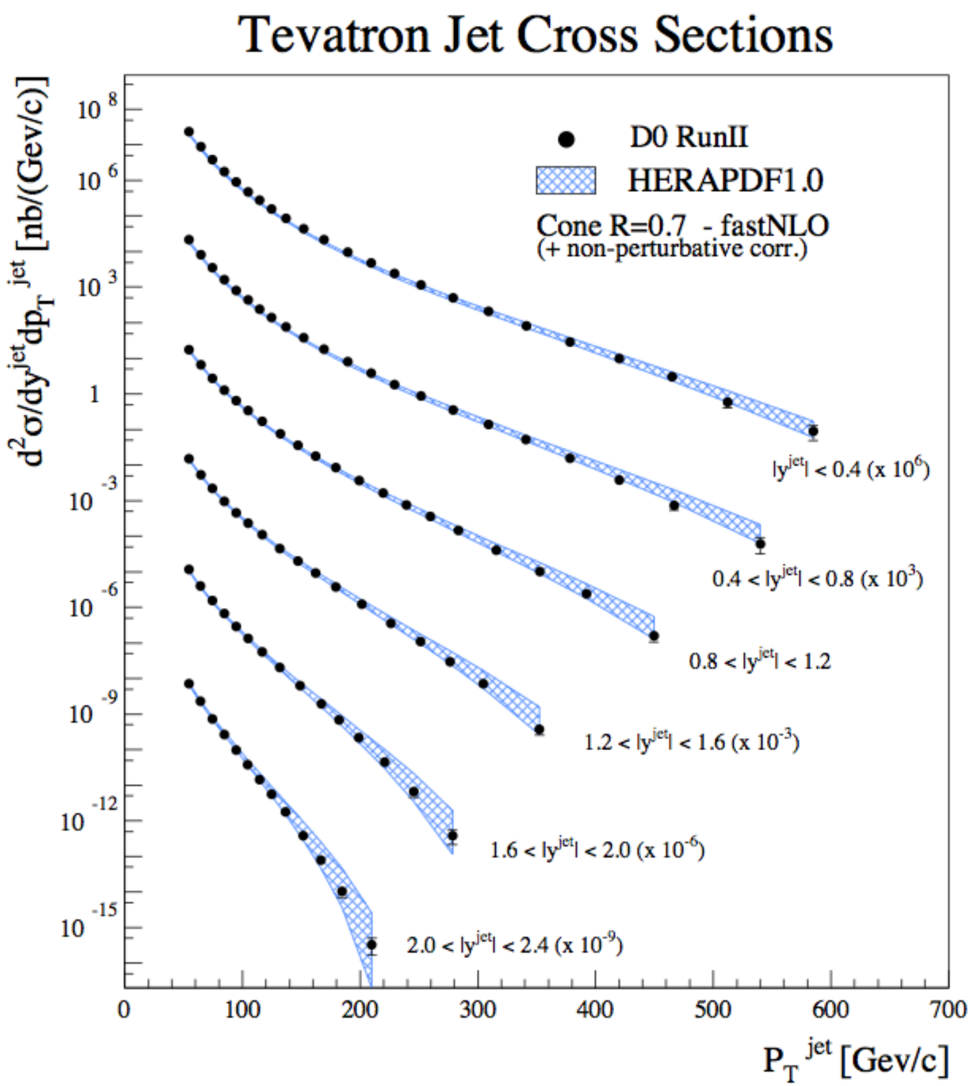
- HERA data are confronted with the first results from the LHC:
  - Quantitative test of the Standard Models: predictions from ep scattering are in good agreement with first observations at pp machine.

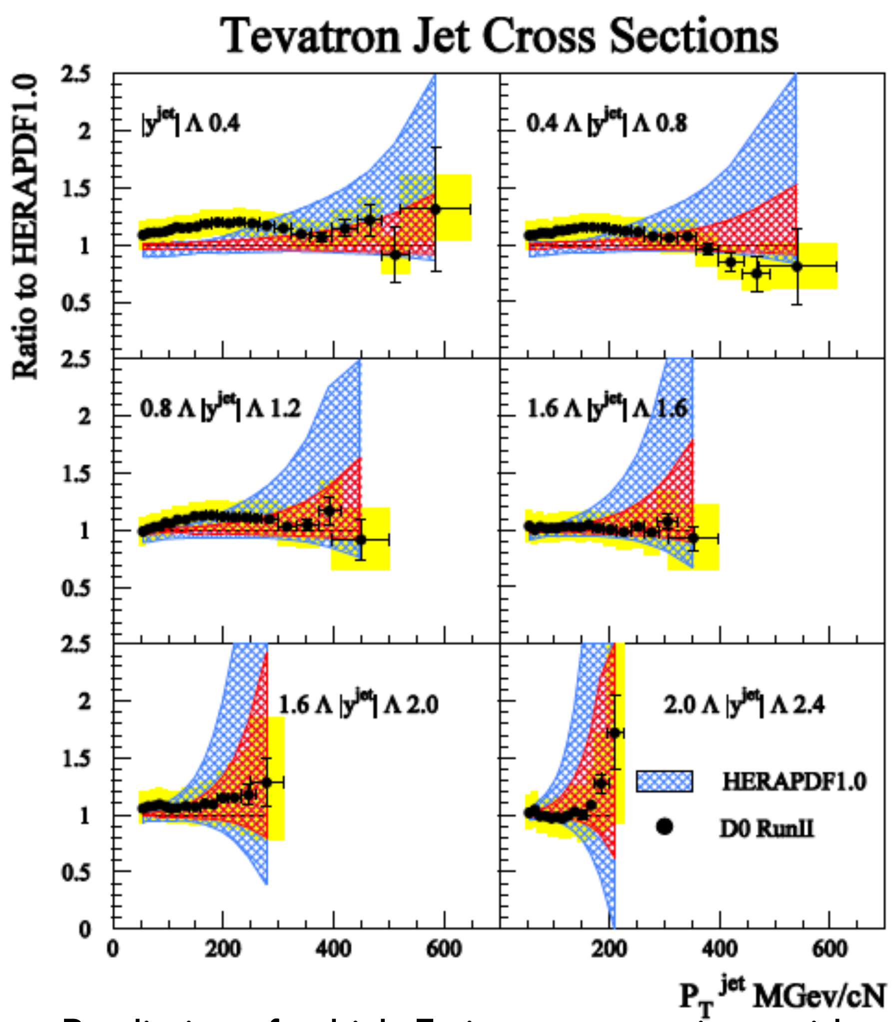
- HERAPDF is a unique platform for understanding the q-g dynamics in the proton by focused studies based on new HERA measurements and for providing predictions free of higher twist and nuclear corrections which are inherent to global fits.

  https://www.desy.de/h1zeus/combined_results/index.php?do=proton_structure

Backup
not necessarily useful

HERAPDF1.0 vs Tevatron Jet Data





- Predictions for high-E_T jet cross-sections with full uncertainties compared to the D0 data
- DIS data from HERA predicts Tevatron jets production from ppbar process.

More on Tevatron Jets

escription of CDF II inclusive jet (k_T) data [hep-ex/0701051]

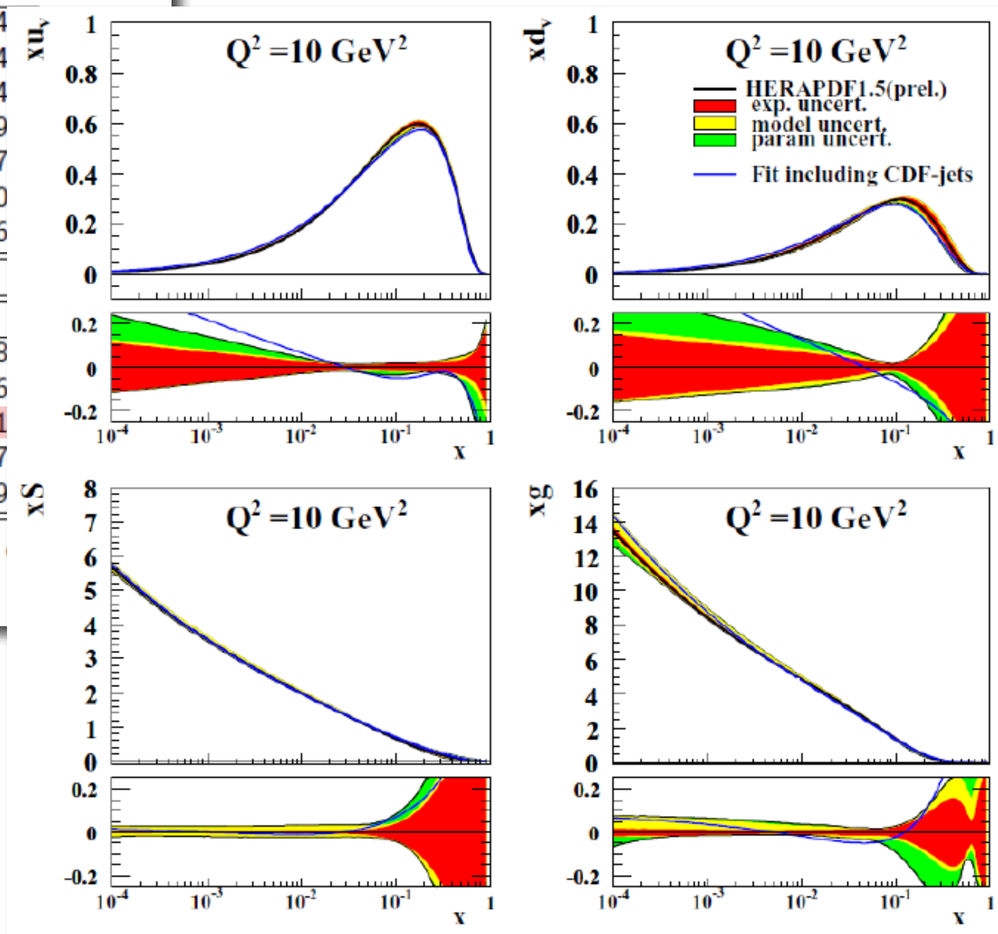
- Values of $\chi^2/N_{\text{pts.}}$ with (without) accounting for correlations:

NLO PDF	$\mu = p_T/2$	$\mu = p_T$	$\mu = 2p_T$
MSTW08	0.75 (0.30)	0.68 (0.28)	0.91 (0.84
CTEQ6.6	1.25 (0.14)	1.66 (0.20)	2.38 (0.84
CT10	1.03 (0.13)	1.20 (0.19)	1.81 (0.84
NNPDF2.1	0.74 (0.29)	0.82 (0.25)	1.23 (0.69
HERAPDF1.0 ($\alpha_S = 0.1176$)	2.43 (0.39)	3.26 (0.66)	4.03 (1.67
ABKM09	1.62 (0.52)	2.21 (0.85)	3.26 (2.10
GJR08	1.36 (0.23)	0.94 (0.13)	0.79 (0.36

NNLO PDF	$\mu = p_T/2$	$\mu = p_T$	$\mu = 2p_T$
MSTW08	1.39 (0.42)	0.69 (0.44)	0.97 (0.48
HERAPDF1.0 ($\alpha_S = 0.1145$)	2.64 (0.36)	2.15 (0.36)	2.20 (0.46
HERAPDF1.0 ($\alpha_S = 0.1176$)	2.24 (0.35)	1.17 (0.32)	1.23 (0.31
ABKM09	2.55 (0.82)	2.76 (0.89)	3.41 (1.17
JR09	0.75 (0.37)	1.26 (0.41)	2.21 (0.49

- Similar trends for CDF II (cone) data and DØ II (cone)

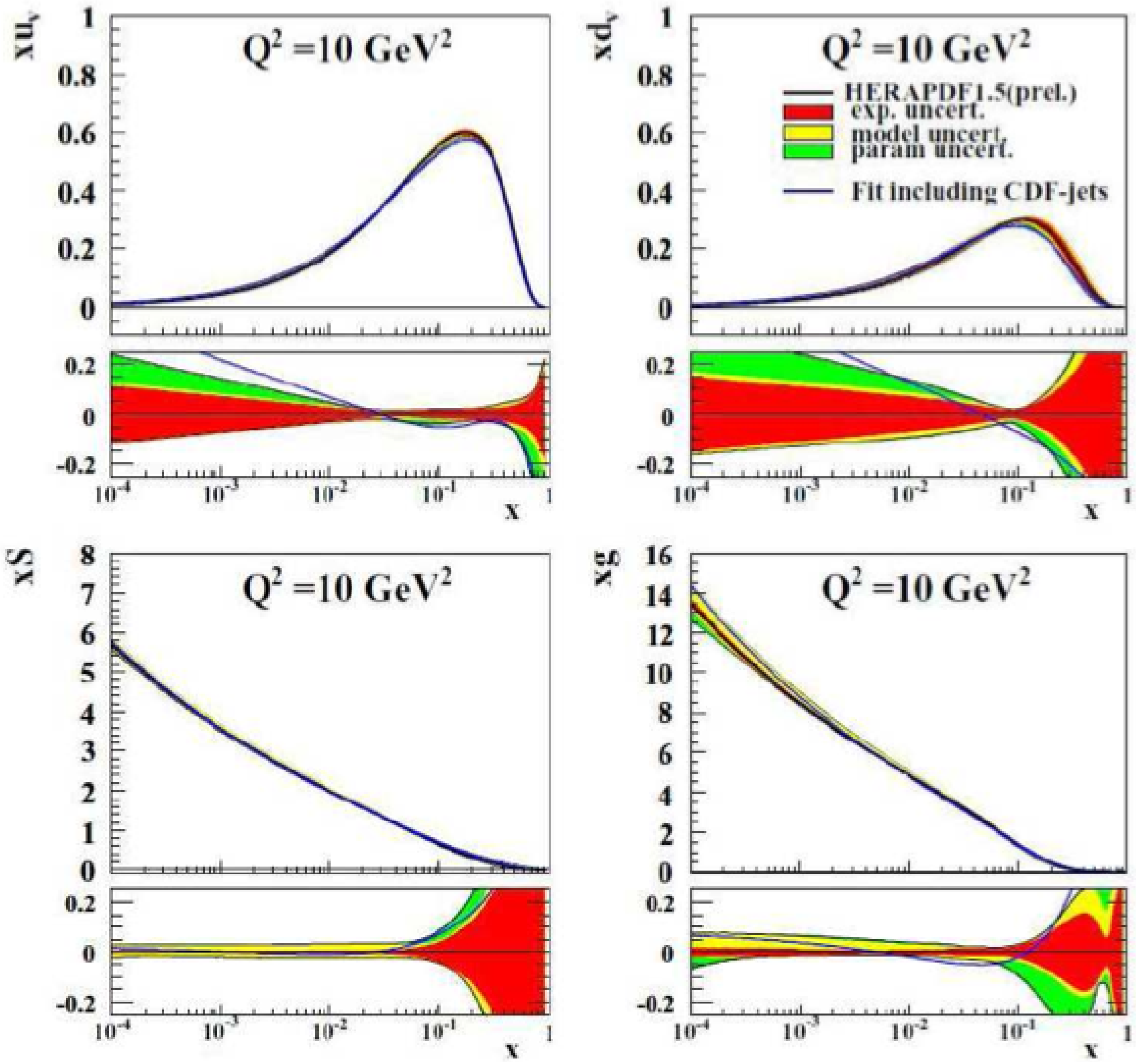
Table from G Watt



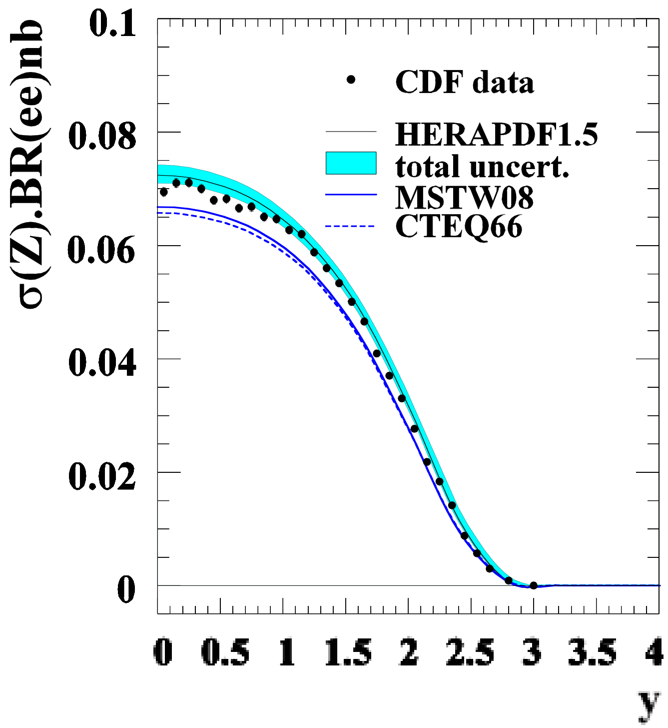
- Based on HERAPDF1.5 (NLO):
  - NO fit : 176/76 (central line)
    - Similar to HERAPDF1.0 due to the same high x gluon between 1.0 and 1.5
  - After fit: 113/76
- HERAPDF1.5 NLO describes Tevatron Data within uncertainties!
- HERAPDF1.5 NNLO: NO fit: 72/76

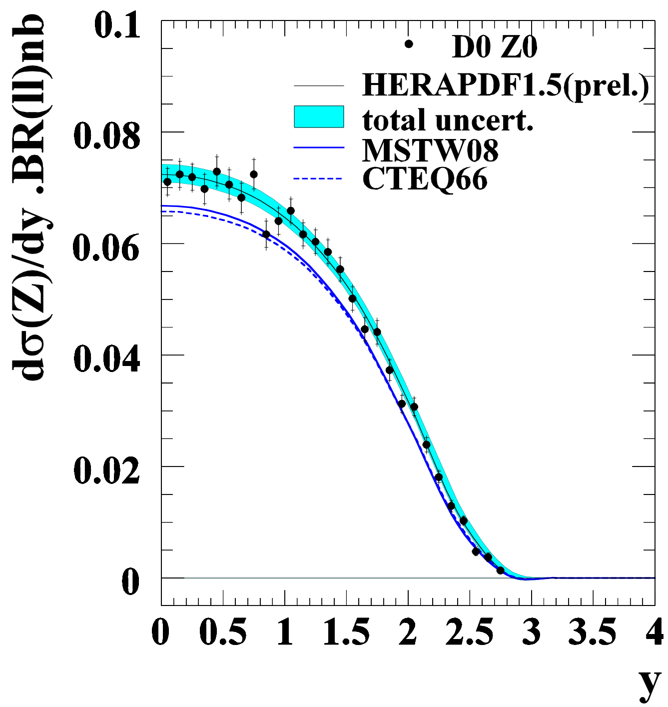
Tevatron jets

- Tevatron jet data provides additional constraints on gluon at high x.
- HERAPDF1.5 provides "reasonable" description of the data.
- Putting the data in the fit gives $\chi^2/dof = 113/76$.



HERAPDF predictions vs Tevatron: Z rapidity



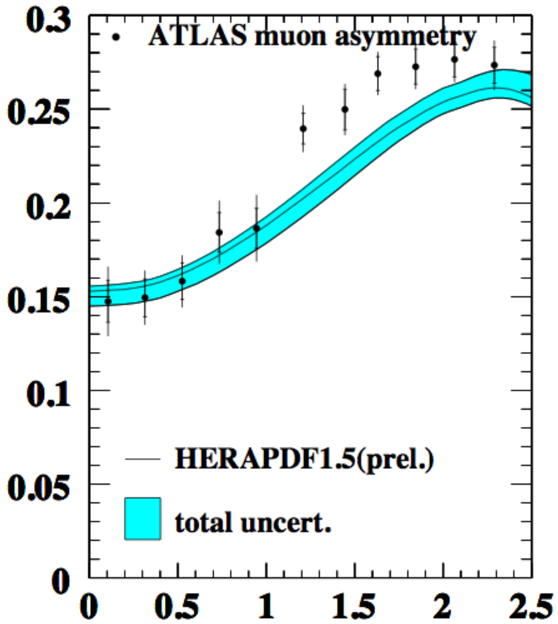


- The description of CDF and D0 Z rapidity by HERAPDF1.5 is good:
  - Without fitting these data (without taking into account PDF uncertainties):
    - $\chi 2$/dof=36/28 CDF - more precise data
    - $\chi 2$/dof=23/28 D0
  - After fitting these data:
    - $\chi 2$/dof=27/28 CDF
    - $\chi 2$/dof=16/28 D0

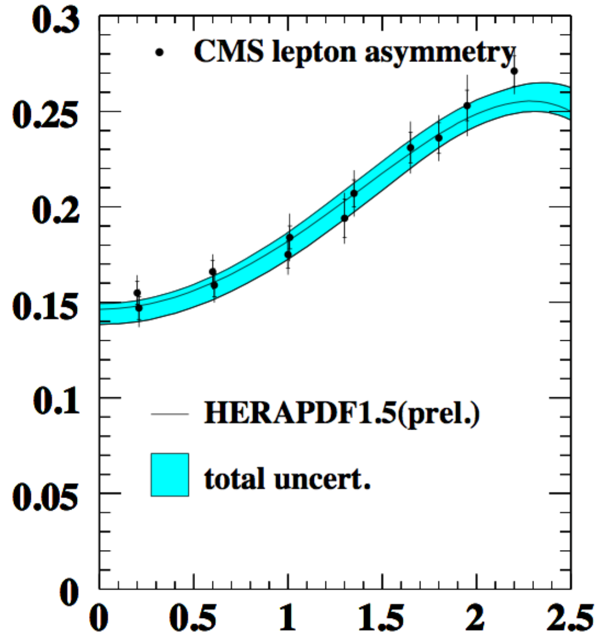
→ Question is: does this fit lies within the uncertainties of HERAPDF1.5?

ATLAS and CMS W charge lepton asymmetries

- HERAPDF1.5 predictions confronted with LHC W charged asymmetry data:



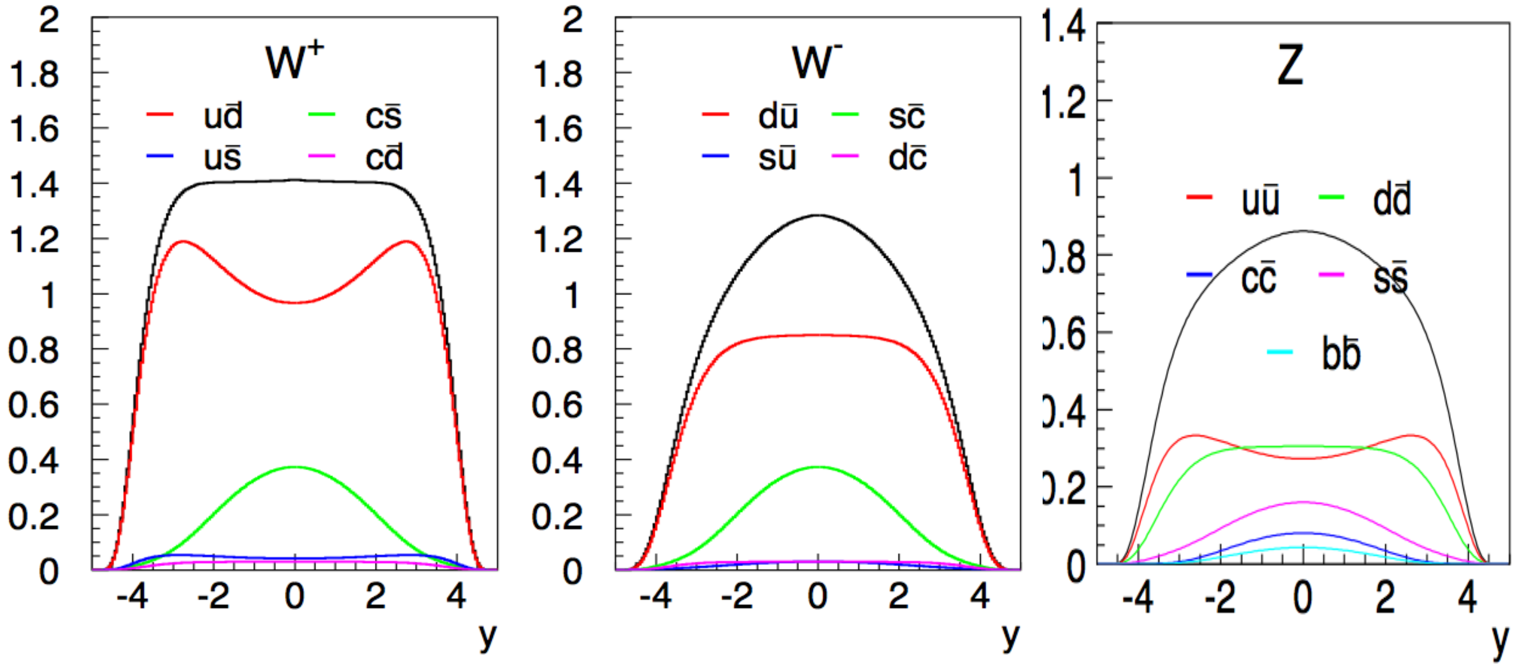
$P_{t,e} > 20$ GeV, $P_{t,miss} > 25$ GeV

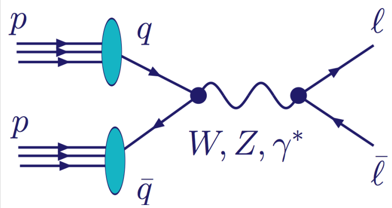


$P_{t,e} > 25$ GeV

- HERAPDF1.5 provides good description of the CMS data and not so good for ATLAS data:
  - Without including data in the fits: After including data in the fits:
    - CMS: $\chi 2$/dof=6.5/12 (muon and electron channels) 4.5/12
    - ATLAS: $\chi 2$/dof=30/11 (only muon channel) 16/11

Decomposition of W and Z at the LHC





<u>Flavour decomposition:</u>

For Ws:

- ud dominates for W
- u_{val} peaks at large rapidity
- sc important at mid y

$$W^+ \sim 0.95(u\bar{d} + c\bar{s}) + 0.05(u\bar{s} + c\bar{d})$$
$$W^- \sim 0.95(d\bar{u} + s\bar{c}) + 0.05(d\bar{c} + s\bar{u})$$

For Z:

- all flavours contribute, even b is significant
- larger coupling to d compared to u

$$Z \sim 0.29(u\bar{u} + c\bar{c}) + 0.37(d\bar{d} + s\bar{s} + b\bar{b})$$
$$\gamma^* \sim 0.44(u\bar{u} + c\bar{c}) + 0.11(d\bar{d} + s\bar{s} + b\bar{b})$$