Structure Function Measurements at HERA and their impact for the LHC

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On Behalf of the H1 and ZEUS Collaborations

2011 Lake Louise Winter Institute

The HERA Collider

World's only ep collider (Desy-Hamburg)
Data taking: Fall 1992 - June 2007

$e^{\pm}$ (27.5 GeV)   p (820/920 GeV)

<u>HERA-I (1992-2000)</u>
L ~ 130 pb^{-1}/experiment
Mostly e^{+}p

<u>HERA-II (2003-2007)</u>
L~360 pb^{-1}/experiment
Similar amounts of e^{+}p and e^{-}p
Long. polarized lepton beams (P~0.35)
Last months: Runs at reduced $\sqrt{s}$ for F_L

HERA delivered
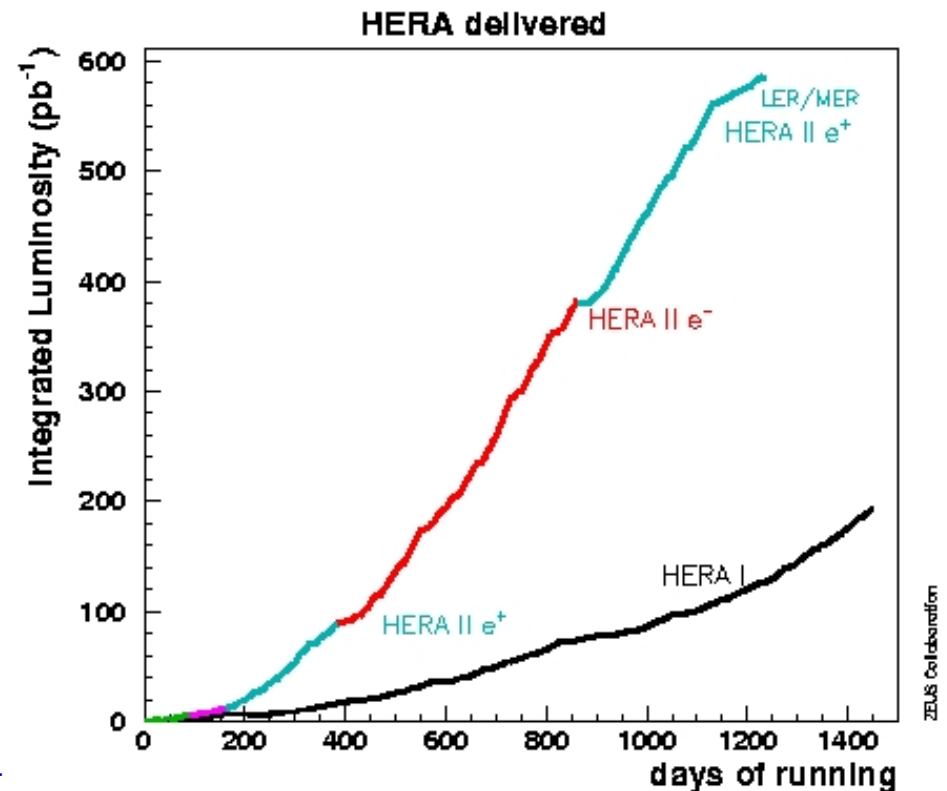
HERA and the Structure of the Proton

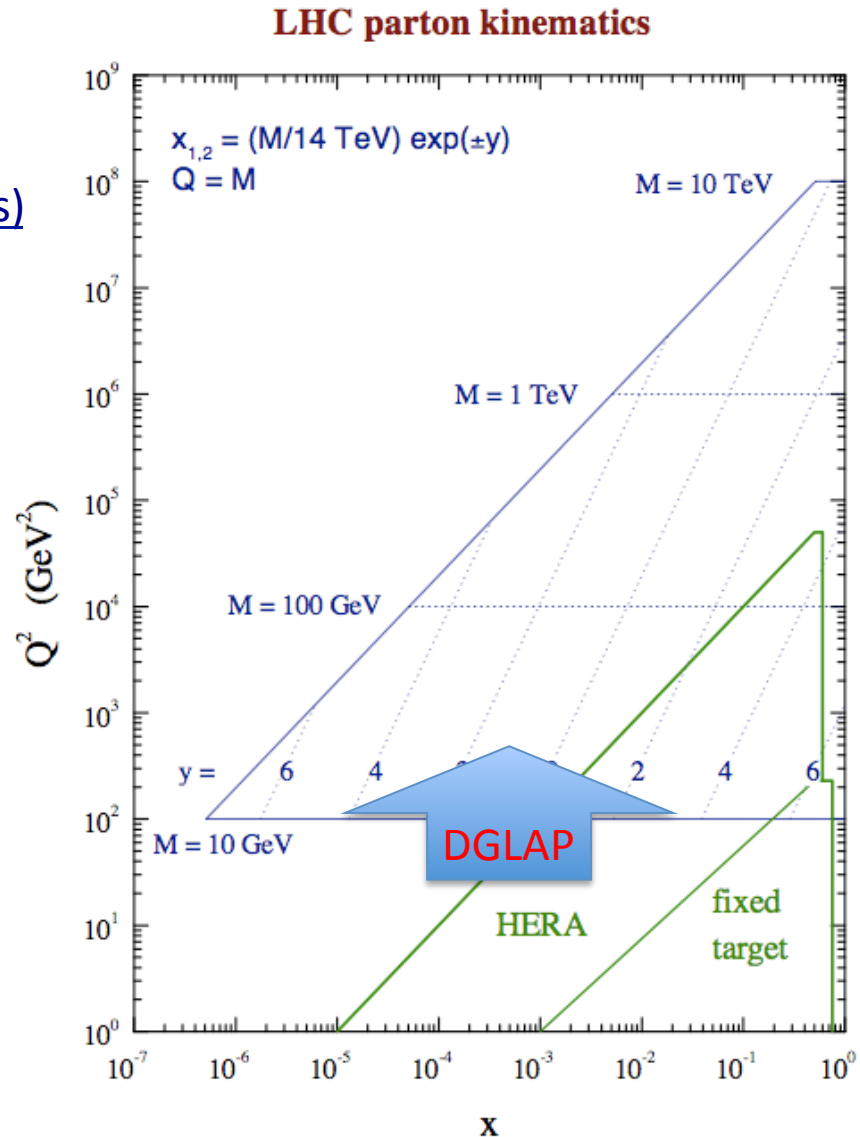HERA data is our main source of knowledge on proton structure:

→ proton's parton distribution functions (PDFs)

Combine the H1 and ZEUS data in order to provide the most precise input to DGLAP analyses

Assume validity of (N)NLO DGLAP equations and extrapolate HERA results into the LHC region
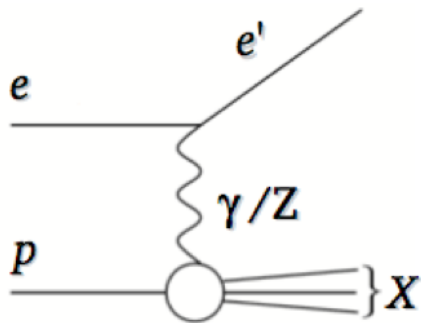
Due to QCD factorization, a very precise determination of the PDFs is crucial for:

- Very stringent tests of the Standard Model
- Searches of Physics Beyond the SM (need to control QCD Background)
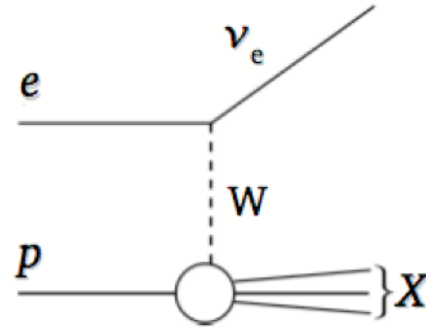

LHC parton kinematics

$x_{1,2} = (M/14\ \text{TeV}) \exp(\pm y)$
$Q = M$

$M = 10\ \text{TeV}$
$M = 1\ \text{TeV}$
$M = 100\ \text{GeV}$
$M = 10\ \text{GeV}$

Q^2 (GeV^2)

$y = $ 6 4 2 4 6

DGLAP

HERA

fixed target

x

DIS processes and cross sections

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

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

Kinematic variables:

- Virtuality exchanged boson

$$Q^2 = -q^2 = -(k - k')^2$$

- Bjorken scaling variable

$$x = \frac{Q^2}{2p \cdot q}$$

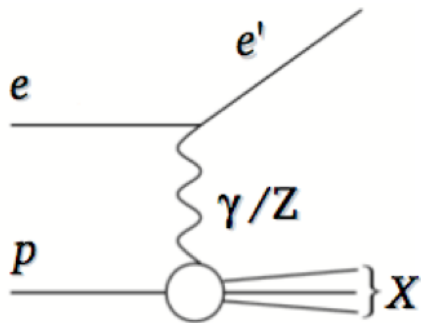Double differential and "reduced" cross sections:

NC: $\sigma_{r,\mathrm{NC}}^{\pm} = \dfrac{d^2\sigma_{\mathrm{NC}}^{e^{\pm}p}}{dx\,dQ^2} \cdot \dfrac{Q^4 x}{2\pi\alpha^2 Y_+} = F_2 \mp \dfrac{Y_-}{Y_+} x F_3 - \dfrac{y^2}{Y_+} F_L$

CC: $\sigma_{r,\mathrm{CC}}^{\pm} = \dfrac{d^2\sigma_{\mathrm{CC}}^{e^{\pm}p}}{dx\,dQ^2} \cdot \dfrac{2\pi x}{G_F^2}\left[\dfrac{M_W^2 + Q^2}{M_W^2}\right]^2 = \dfrac{1}{2}\left(Y_+ W_2^{\pm} \mp Y_- x W_3^{\pm} - y^2 W_L^{\pm}\right)$
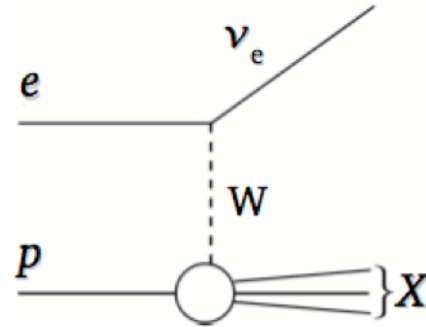
with $Y_{\pm} = 1 \pm (1-y)^2$

DIS processes and cross sections

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

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<u>Kinematic variables:</u>

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$$x = \frac{Q^2}{2p \cdot q}$$

<u>Structure Functions, PDFs and DGLAP evolution equations:</u>

$$x^{-1} F_2(x, Q^2) = \sum_{i=q,g} \int_x^1 \frac{d\xi}{\xi} C_{2,i}\left(\frac{x}{\xi}, \alpha_s(\mu^2), \frac{\mu^2}{Q^2}\right) f_i(\xi, \mu^2)$$
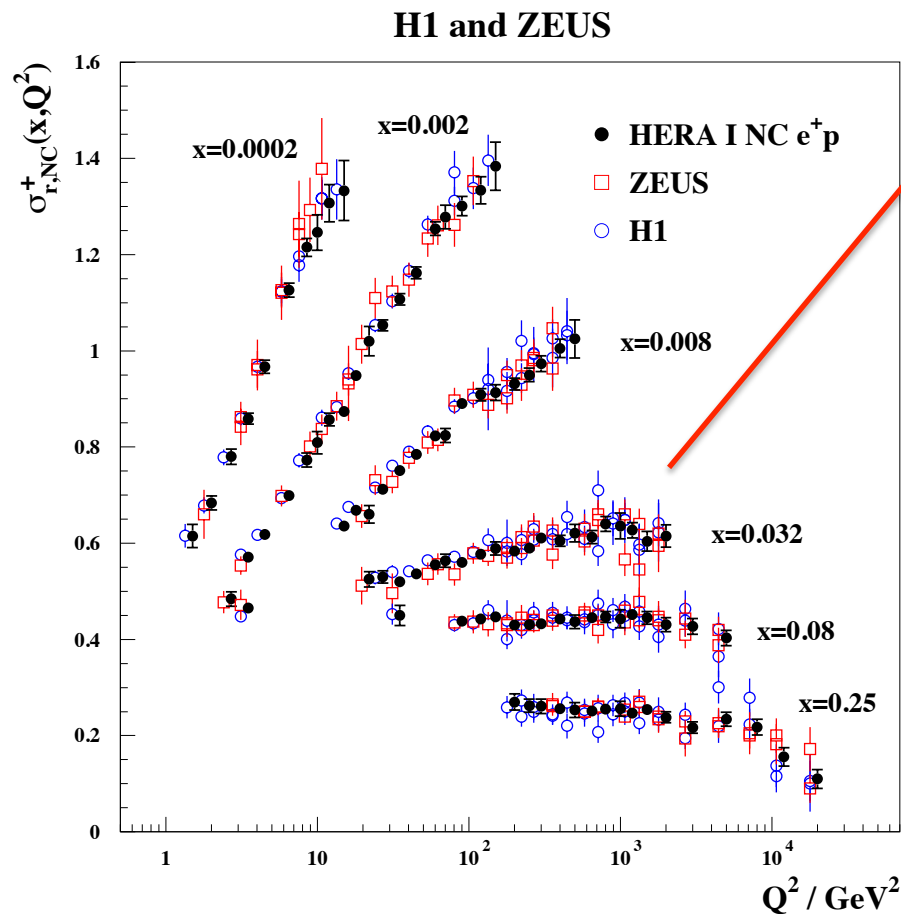
$$\frac{d}{d\ln\mu^2} f_i(\xi, \mu^2) = \sum_k \left[P_{ik}(\alpha_s(\mu^2) \otimes f_k(\mu^2)) \right](\xi)$$

Results I will Cover

- Combination of the H1 and ZEUS data and DGLAP fits:

  - HERA-I inclusive cross sections:
    - Precise determination of the sea quarks and gluons at mid- and low-x

    JHEP 1001:109(2010)

  - HERA-I + F_2(charm) data:
    - Constraints on the charm mass and study of different heavy quarks schemes

  - HERA-I + low energy data:
    - Longitudinal structure function
    - Impact of these low-x, low-Q^2 data on PDFs

  - HERA-I+HERA-II Inclusive cross sections (high-Q^2):
    - Better determination of the valence quarks at high-x

Preliminary

- As an illustration of the above, will show predictions for Tevatron and LHC observables based on HERAPDFs:
 - high-Et Jets, W/Z , Higgs and top

Combination of HERA I data

H1 and ZEUS

Plot axes: $\sigma^+_{r,NC}(x,Q^2)$ versus Q^2 / GeV^2

Legend:
- ● HERA I NC e^+p
- □ ZEUS
- ○ H1

Curve labels: x=0.0002, x=0.002, x=0.008, x=0.032, x=0.08, x=0.25

- **Combined are all published HERA-I NC,CC $e^\pm p$ cross section measurements**
  - 1402 data points
  - 110 syst. error sources (and correlations)
  - details on the χ^2 combination method:
    → see JHEP 1001:109(2010) [arXiv:0904.0929]

- **Data show good consistency:**
  - χ^2/ndof =637/656
  - small shift of global norms
  - distribution of pulls

- **Experiments "cross calibrate" each other**

  - <u>1-2% total uncert. in the low- mid-Q^2 region</u>

Combination of HERA I data

H1 and ZEUS
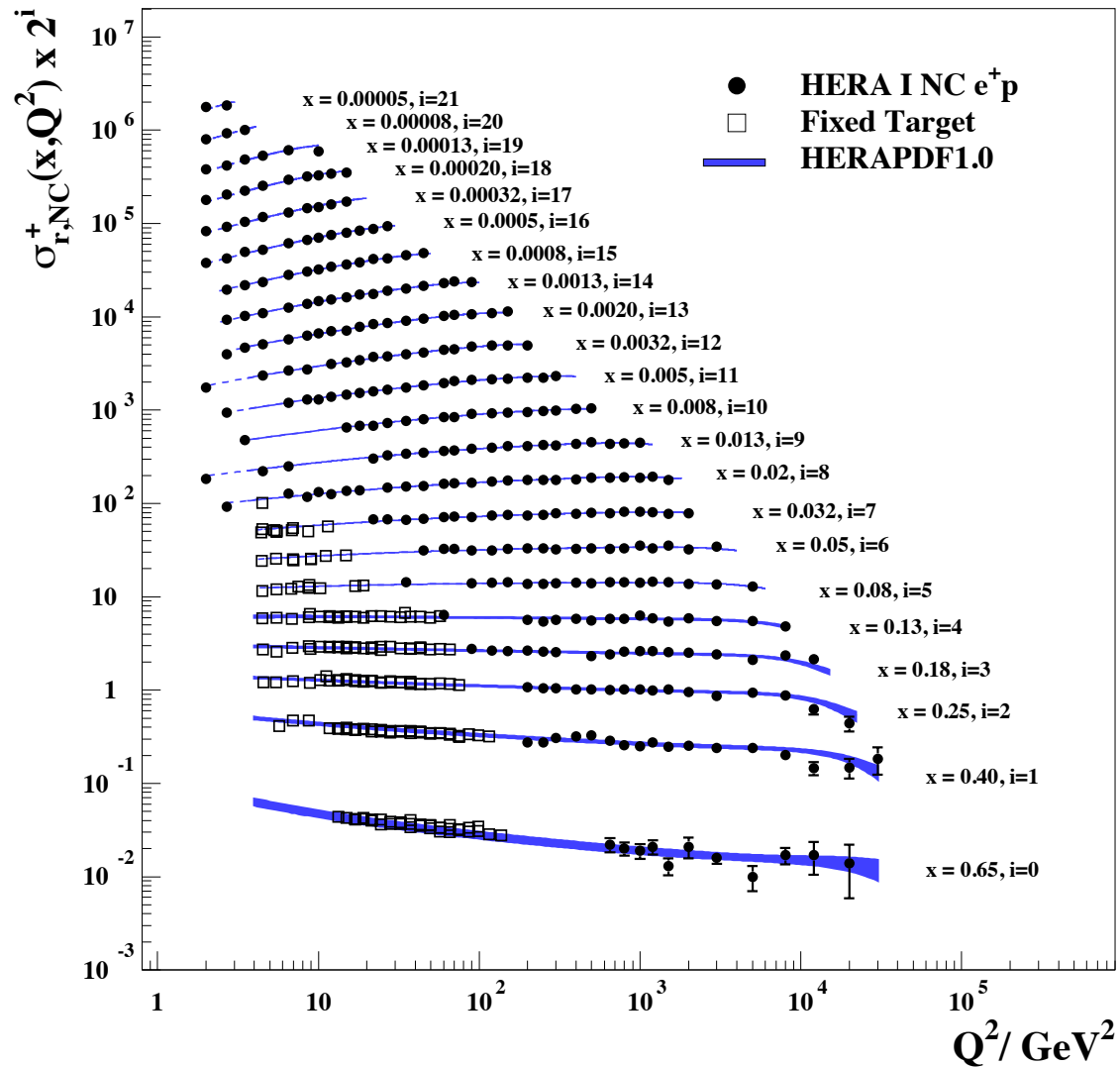
DGLAP Analysis of HERA-I data: HERAPDF 1.0
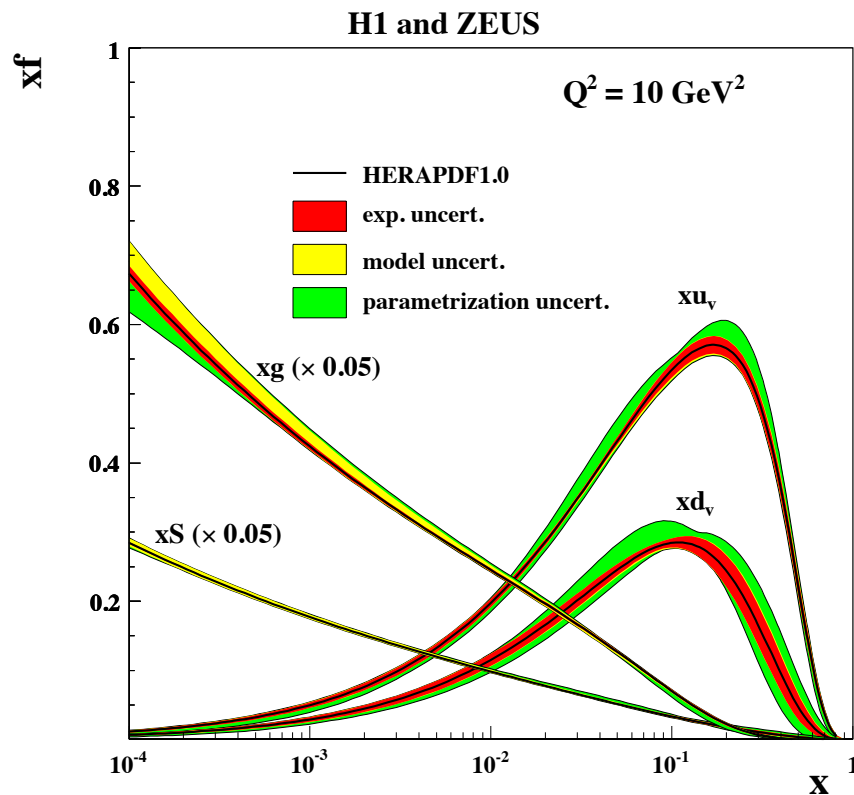
- NLO DGLAP analysis based only on the HERA-I, fully consistent, combined dataset:
  - no need for heavy target/deuterium corrections or strong isospin assumptions
  - $\chi^2/\text{ndof} = 574/582$

- Massive treatment for heavy flavours (RT-VFNS)

- Detailed study of uncertainties:
  - experimental, model and parametrisation

The very precise HERAPDF1.0 set is available in LHAPDF since v5.8.1

DGLAP Analysis of HERA-I data: HERAPDF 1.0

H1 and ZEUS
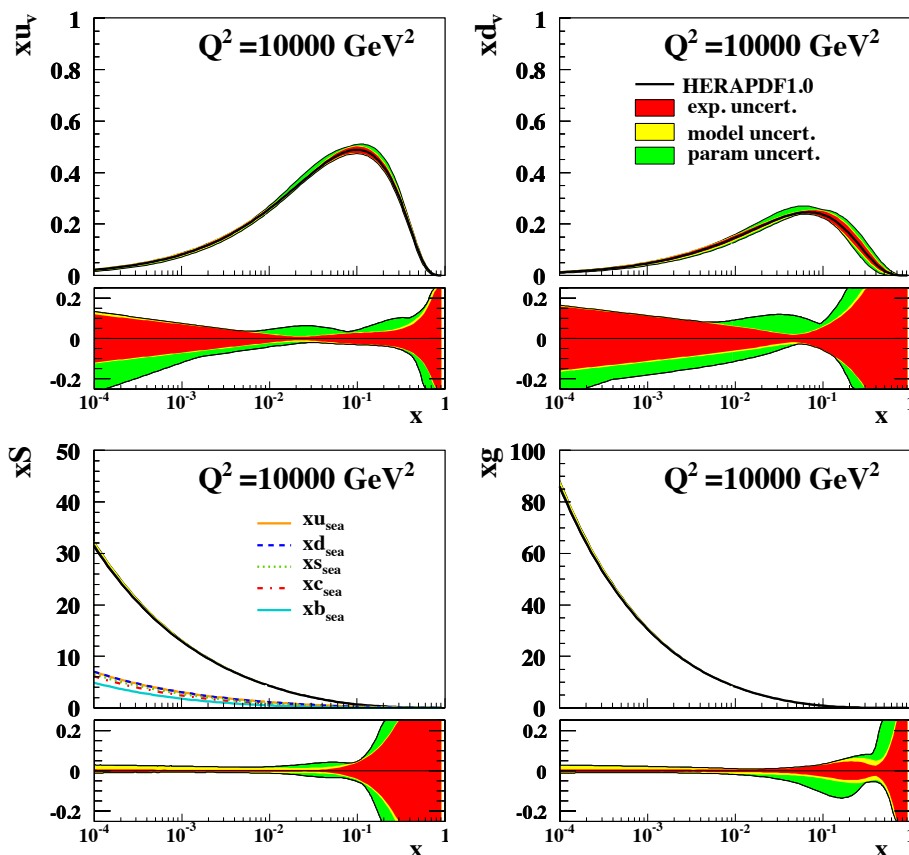
Experimental uncertainty:

Consistent data set ➜ use $\Delta\chi^2 = 1$

Model Uncertainty:

Following variations were 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]

Parametrization uncertainty:

Envelope from DGLAP Fits using variants of the parametrisation form at Q_0^2

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

At the scale $Q^2 = 10\,000$ GeV^2 (relevant to LHC)
the sea and gluon densities are known at the % level for $x \leq 10^{-1}$
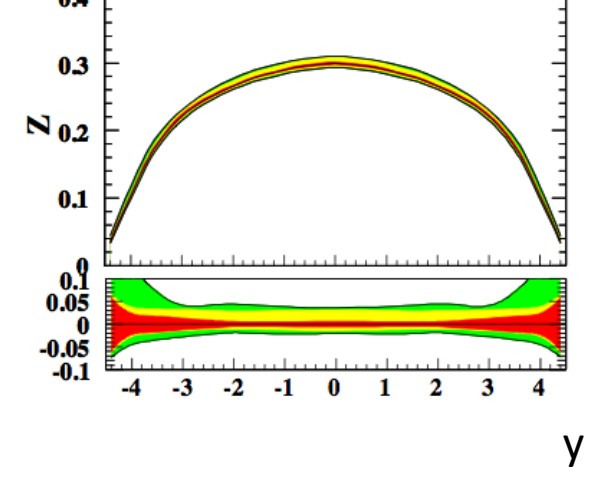
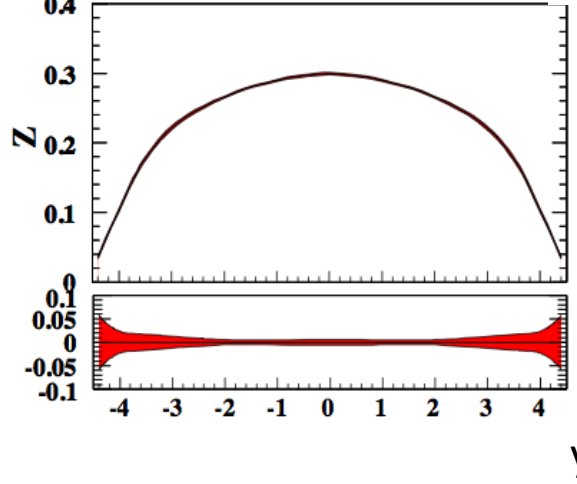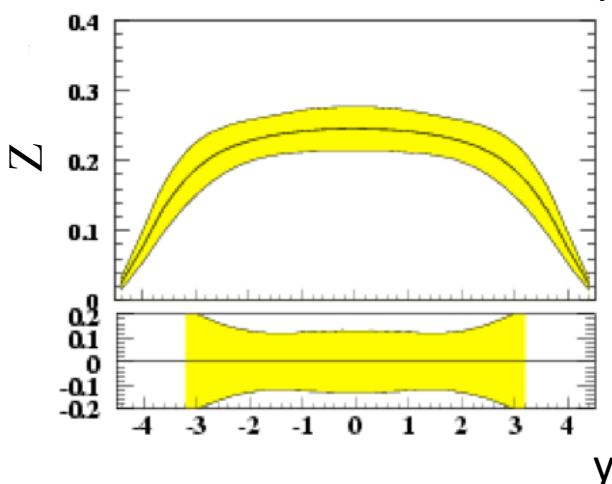# W and Z production at the LHC

√s=14 TeV
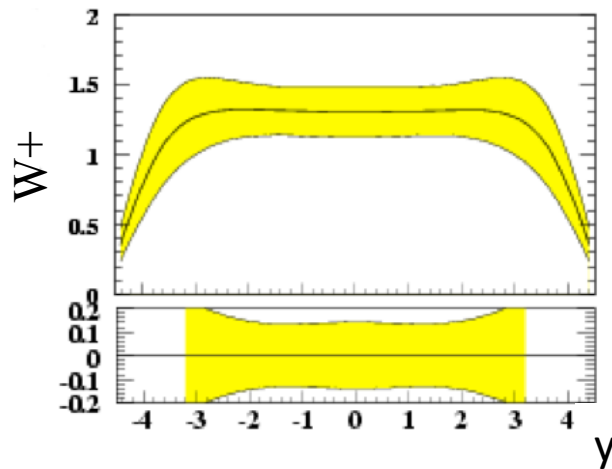
Without HERA data (exp. only)
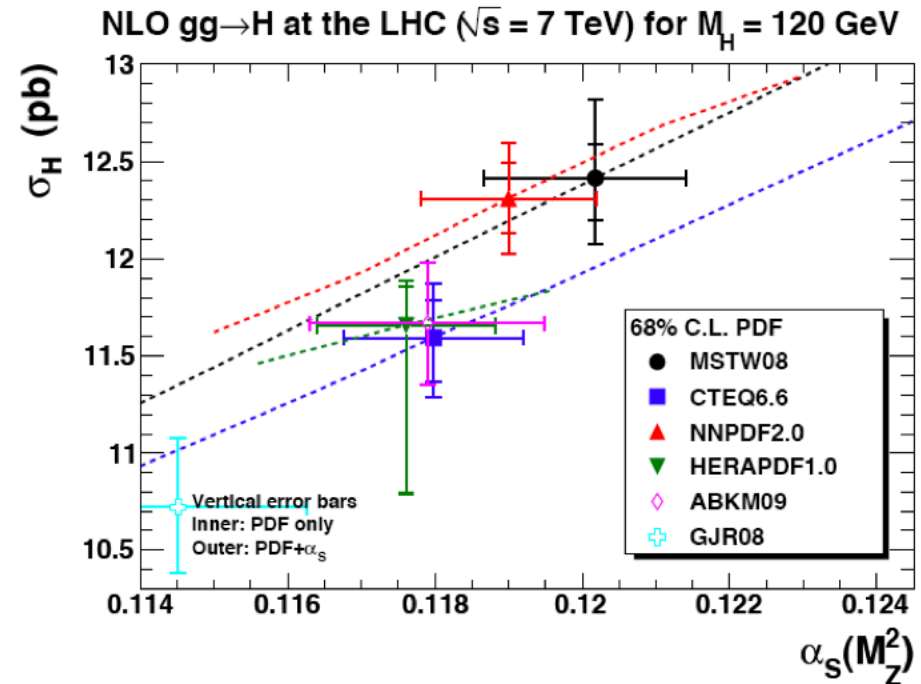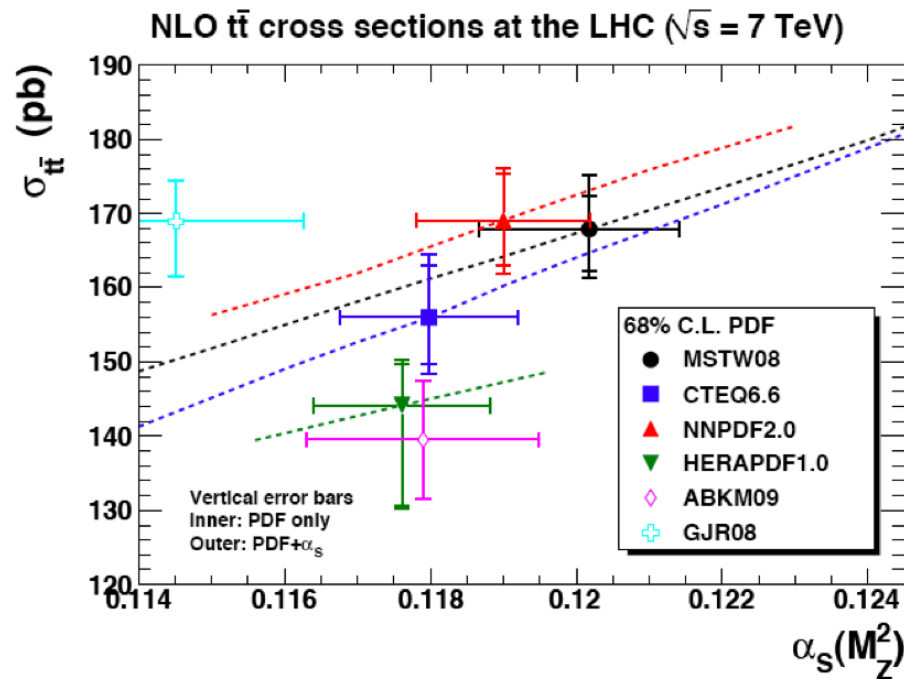~15% uncertainty
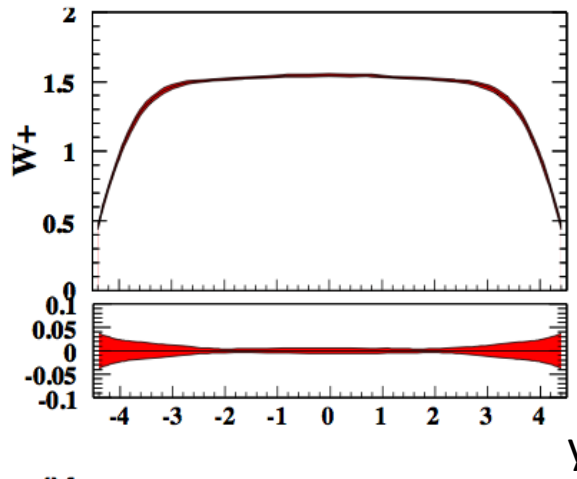
HERAPDF1.0 (exp. only)
~ 1% uncertainty!
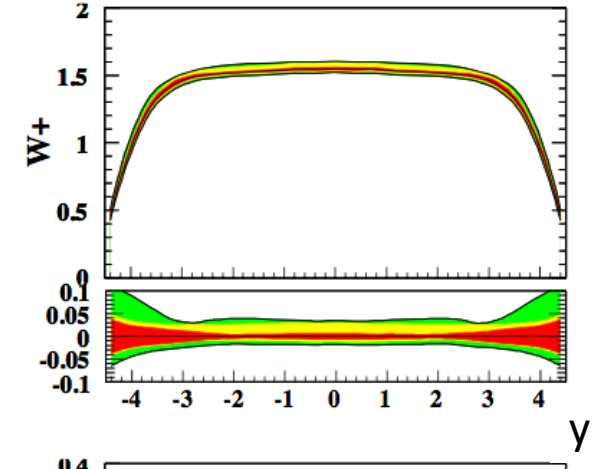
HERAPDF1.0 (total)
~ 5% uncertainty

# Benchmarking PDFs: LHC cross sections

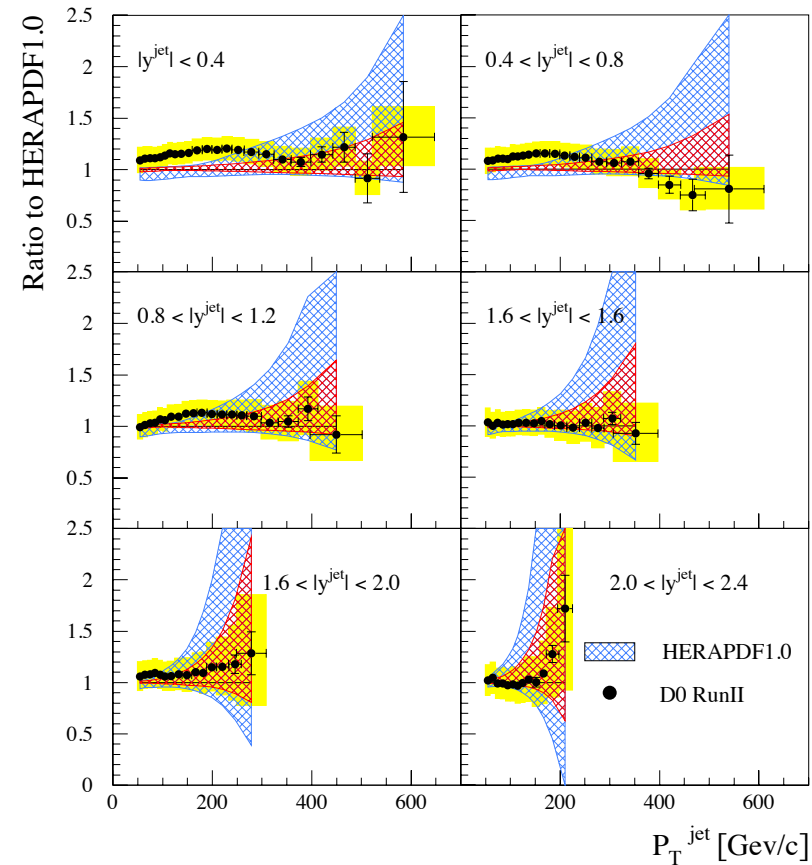e.g. gluon-gluon dependent cross sections such as Higgs and tt̄

- HERA experiments fully involved in this benchmark activity
- HERAPDF1.0 provides realistic uncertainty for LHC cross sections
  (often dominant parameterization uncert. not accounted for in most global fit groups)

HERAPDF1.0 and Tevatron jets
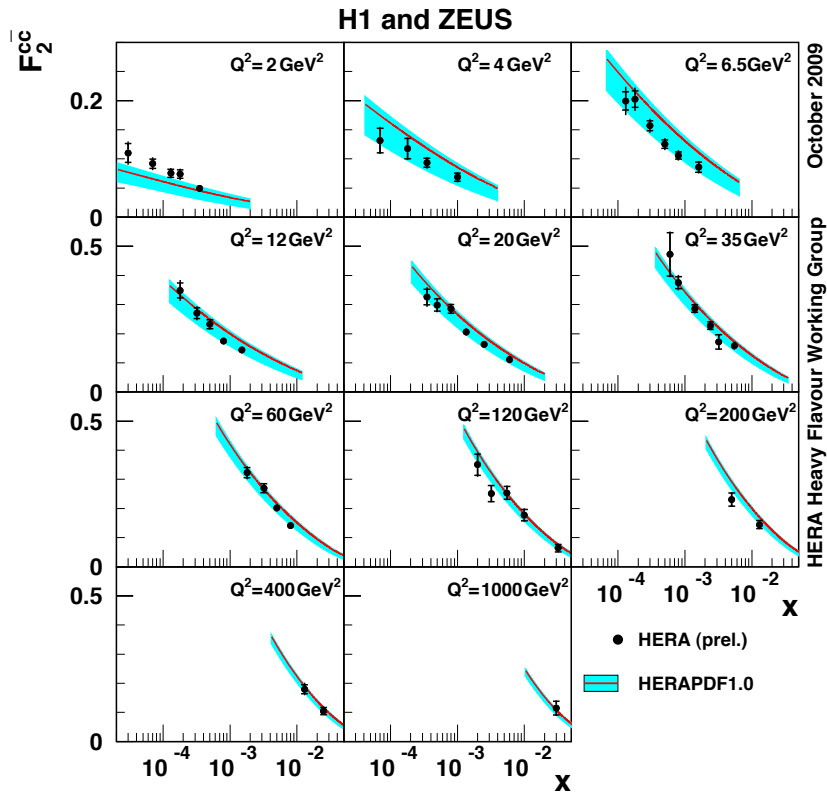

Tevatron Jet Cross Sections
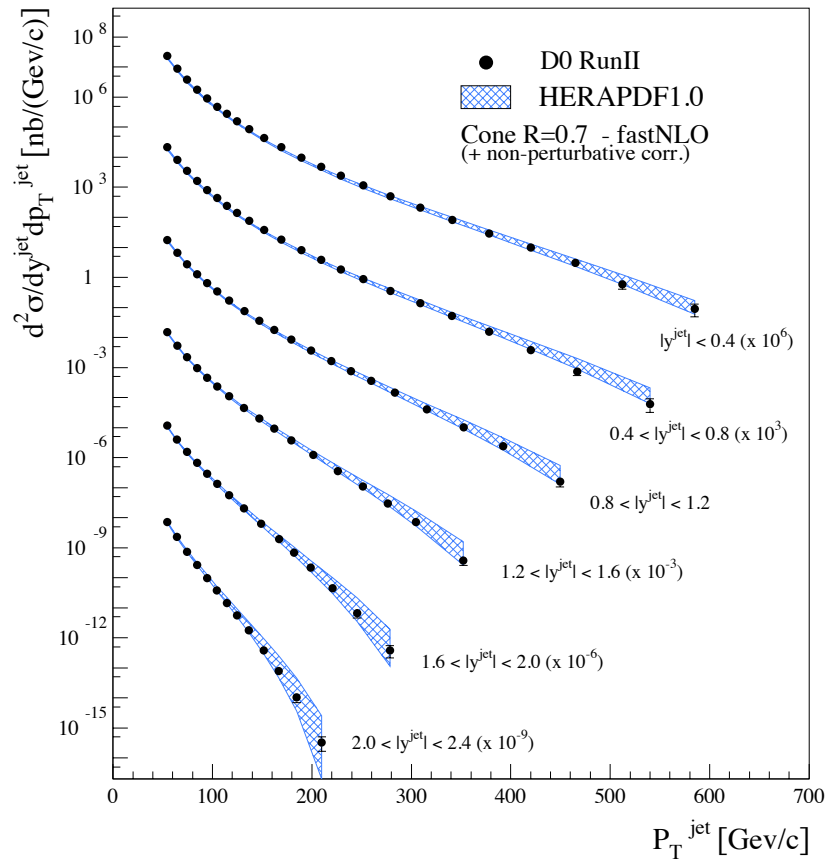
Tevatron Jet Cross Sections

- Predictions based on HERAPDF1.0 agree with Tevatron results
- Test PDF universality and collinear factorization
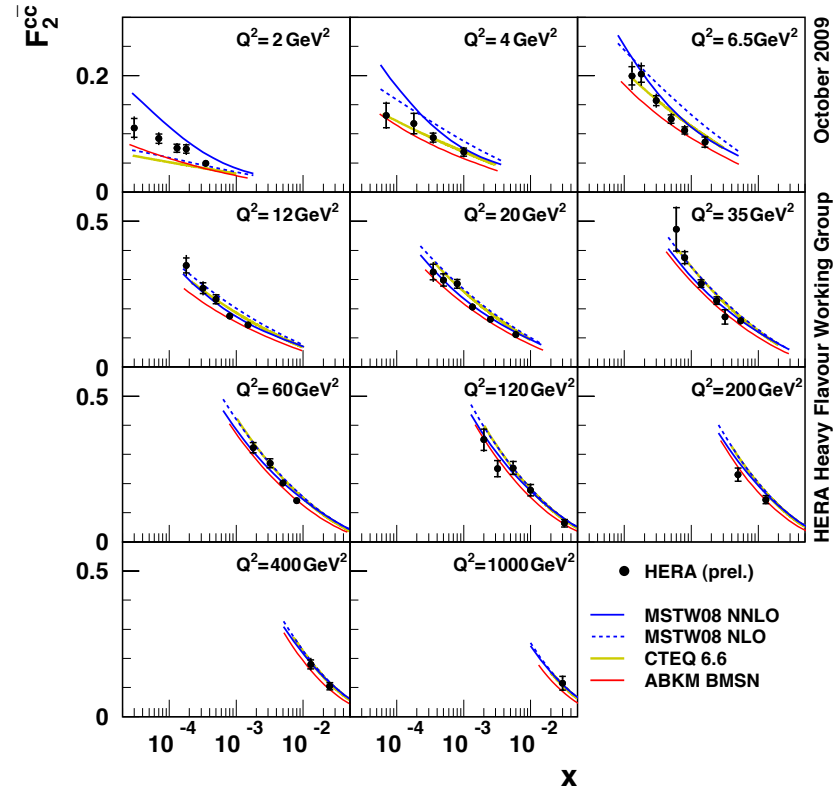- Similar results for W/Z production (not shown)

F$_2$ Charm at HERA

Combine H1 and ZEUS charm data:

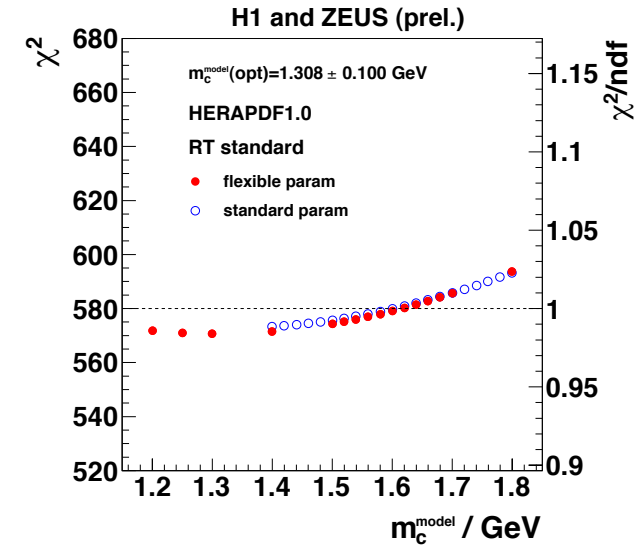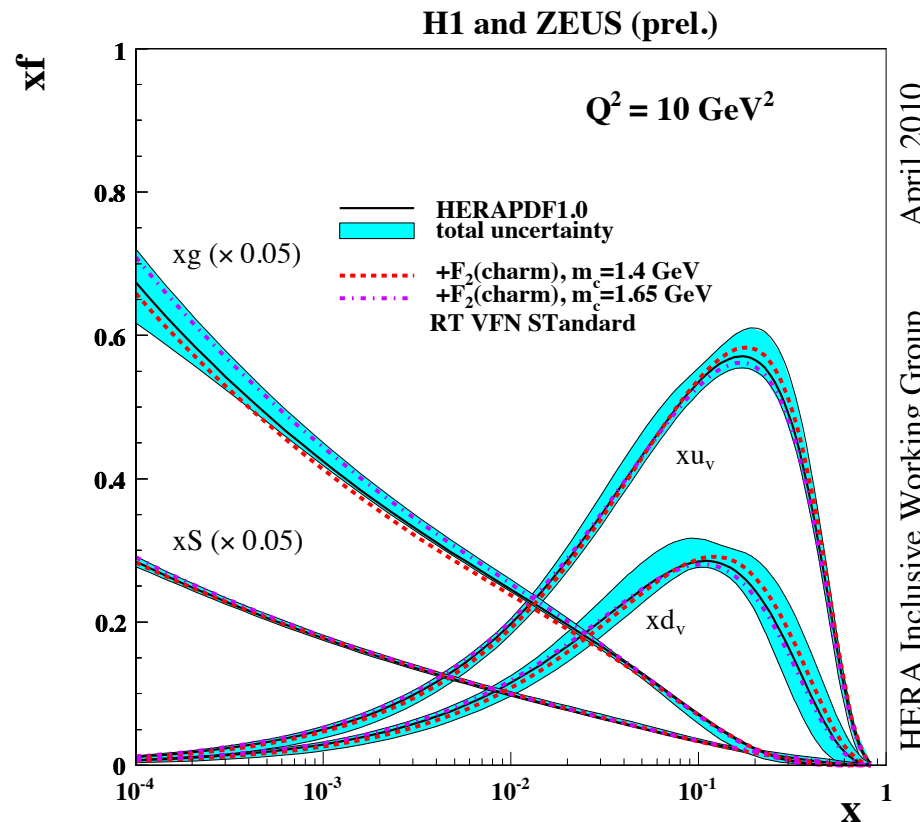Reasonable agreement with QCD prediction, based on HERAPDF1.0, when accounting for uncertainty on m$_c$

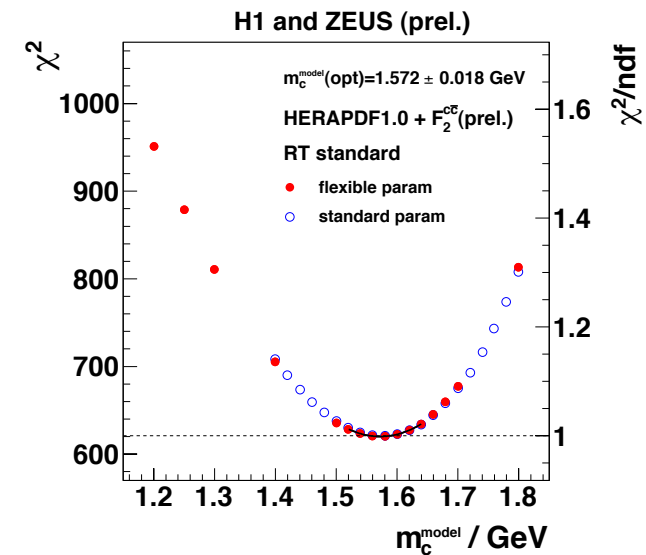Uncertainty band: 1.35 < m$_c$ < 1.65 GeV

Precision of the combined measurements (5-10%) such that we can start to study differences among General Mass Variable Flavour Number Schemes (GM-VFNS)

Including charm data in the HERAPDF fit

...does not change PDF significantly
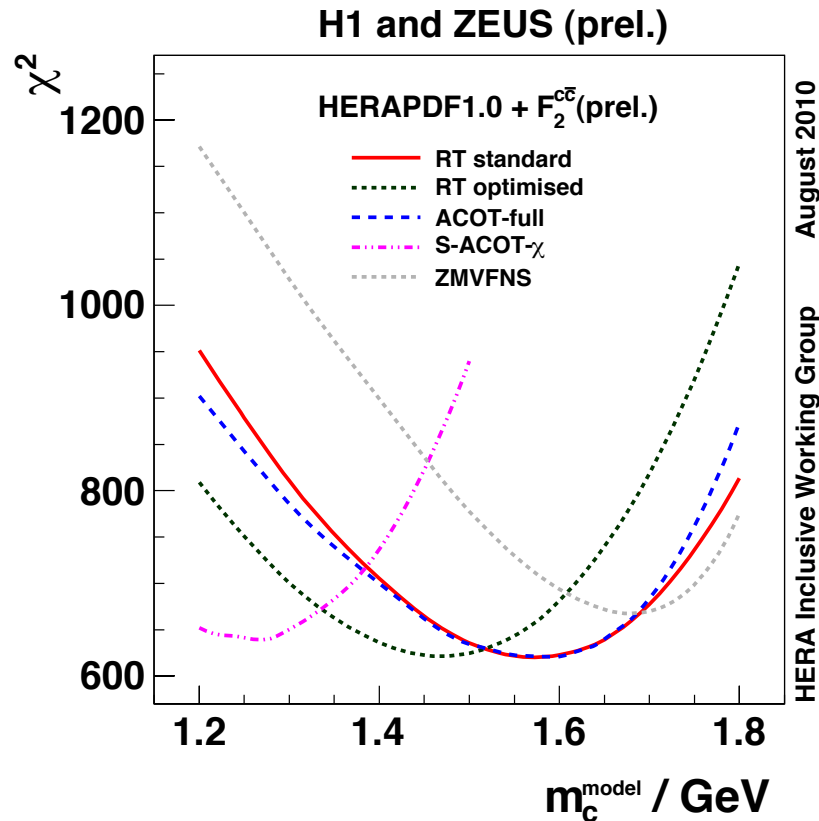but increases sensitivity to charm mass

H1 and ZEUS (prel.)

$Q^2 = 10$ GeV^2

April 2010

xf

xg (× 0.05)

HERAPDF1.0
total uncertainty
+F$_2$(charm), m$_c$=1.4 GeV
+F$_2$(charm), m$_c$=1.65 GeV
RT VFN STandard

xu$_v$

xS (× 0.05)

xd$_v$

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x

H1 and ZEUS (prel.)

χ^2

χ^2/ndf

m$_c^{model}$(opt)=1.308 ± 0.100 GeV

HERAPDF1.0
RT standard
flexible param
standard param

m$_c^{model}$ / GeV

without charm

H1 and ZEUS (prel.)

χ^2

χ^2/ndf

m$_c^{model}$(opt)=1.572 ± 0.018 GeV

HERAPDF1.0 + F$_2^{c\bar{c}}$(prel.)
RT standard
flexible param
standard param

m$_c^{model}$ / GeV

with charm

Charm, VFNS schemes and W predictions at LHC

H1 and ZEUS (prel.)

HERAPDF1.0 + $F_2^{c\bar{c}}$(prel.)

- RT standard
- RT optimised
- ACOT-full
- S-ACOT-χ
- ZMVFNS

August 2010

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W^+ ($\sqrt{s}$ = 7 TeV)
HERAPDF1.0 + $F_2^{c\bar{c}}$(prel.)

Different "optimal" effective masses
for different GM-VFNS yield very similar fits
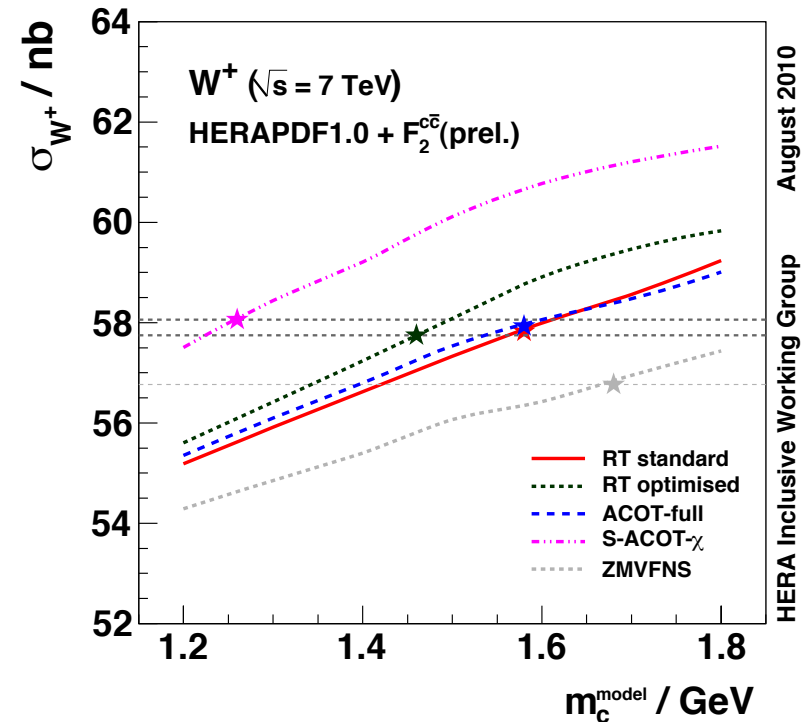
If a fixed "optimal" mass value is considered
then the spread is still considerable (~7%)
but if each prediction is taken at its own
optimal value the spread among predictions
is reduced to 1% (2% considering ZM-VFNS)

Adding low energy data

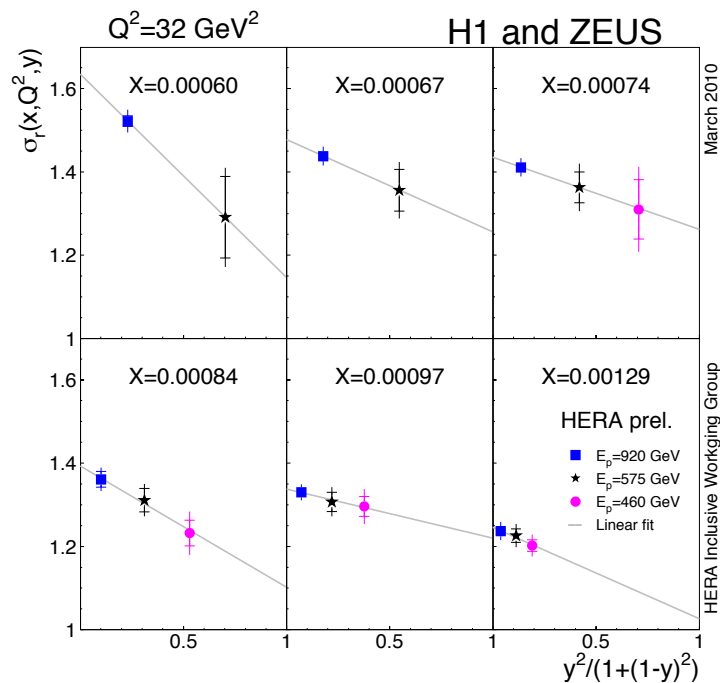Add to HERA-I combined results
measurements @ Ep= 920, 575, 470 GeV
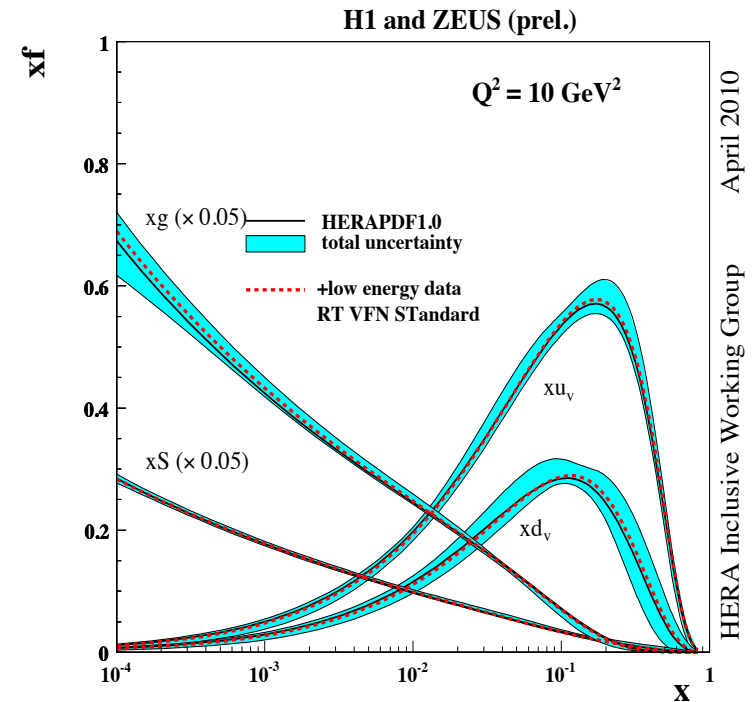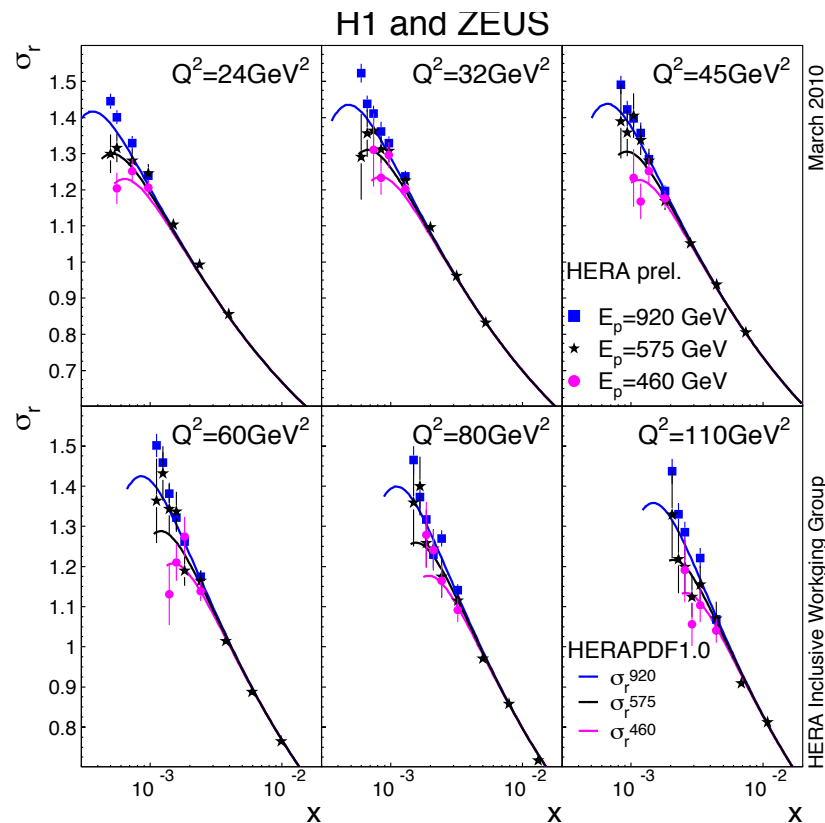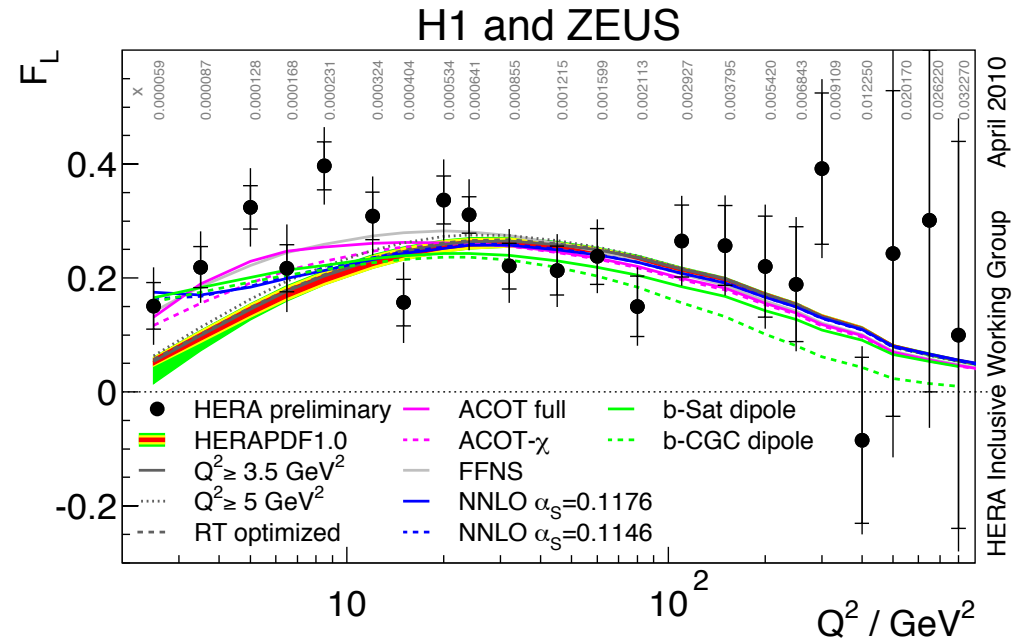

PDFs from new fit agree well with
HERAPDF1.0

..but worse χ^2/ndof at low Q^2 and x

Longitudinal Structure Function

$$\sigma_r = F_2(x, Q^2) - \frac{y^2}{1 + (1-y)^2} F_L(x, Q^2)$$

Determine F_2 and F_L simultaneously from a simple linear fit

Combined F_L in general consistent with HERAPDF1.0 but at low Q^2, the QCD prediction tends to underestimate the measurements.
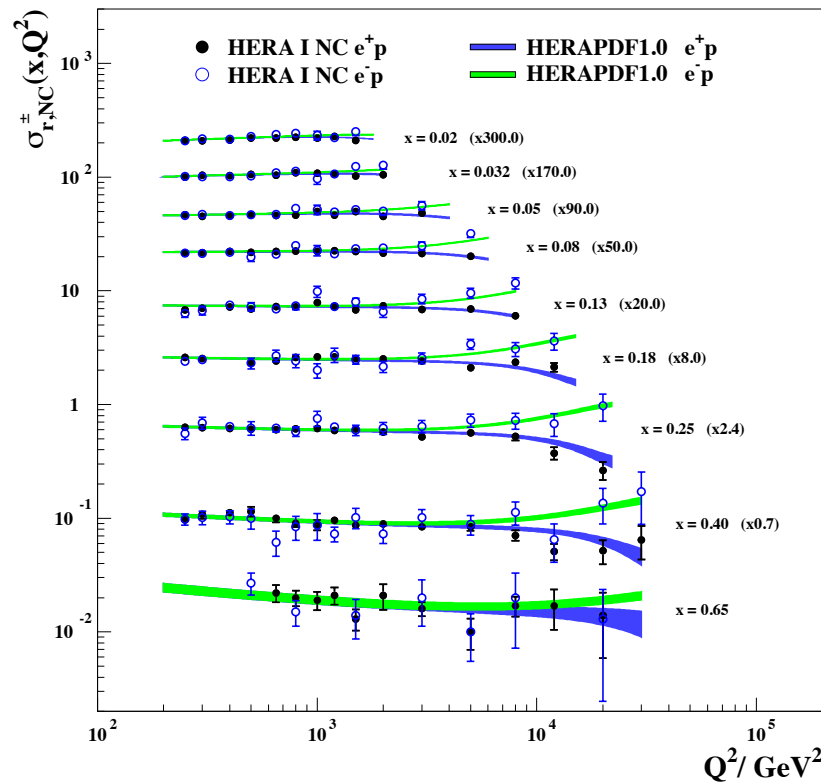
Using NNLO or different heavy flavour schemes may help to improve description

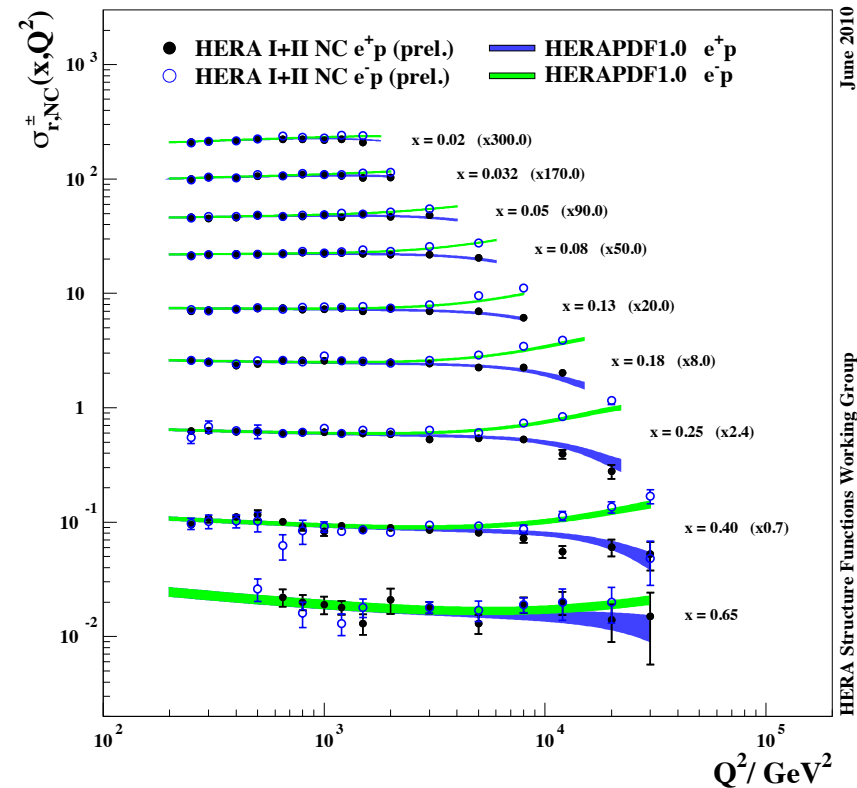# HERA-II High-Q^2 Data: NC e$^{\pm}$p

HERA-I combined results
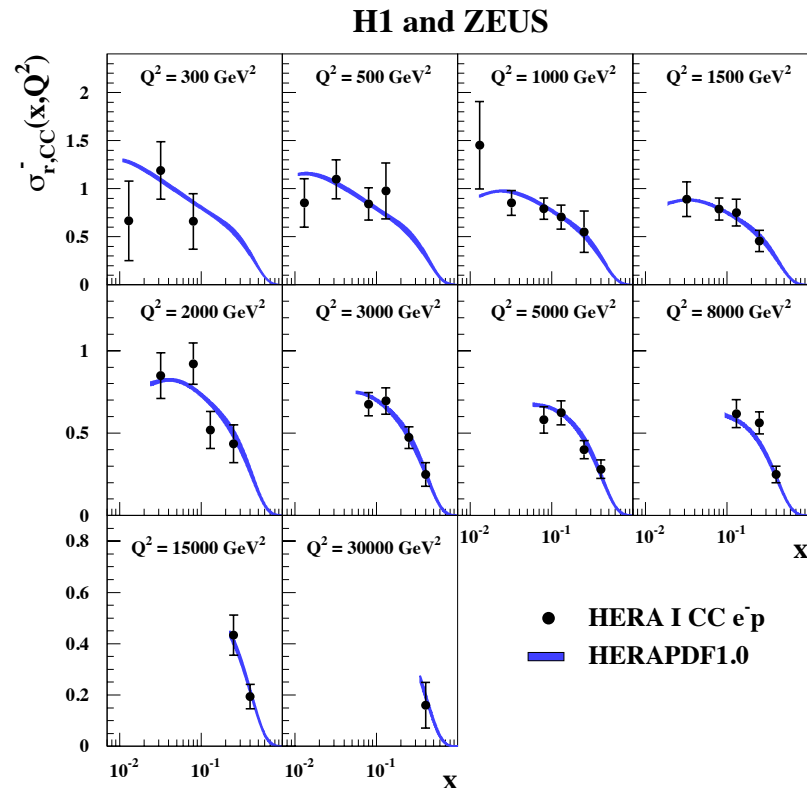
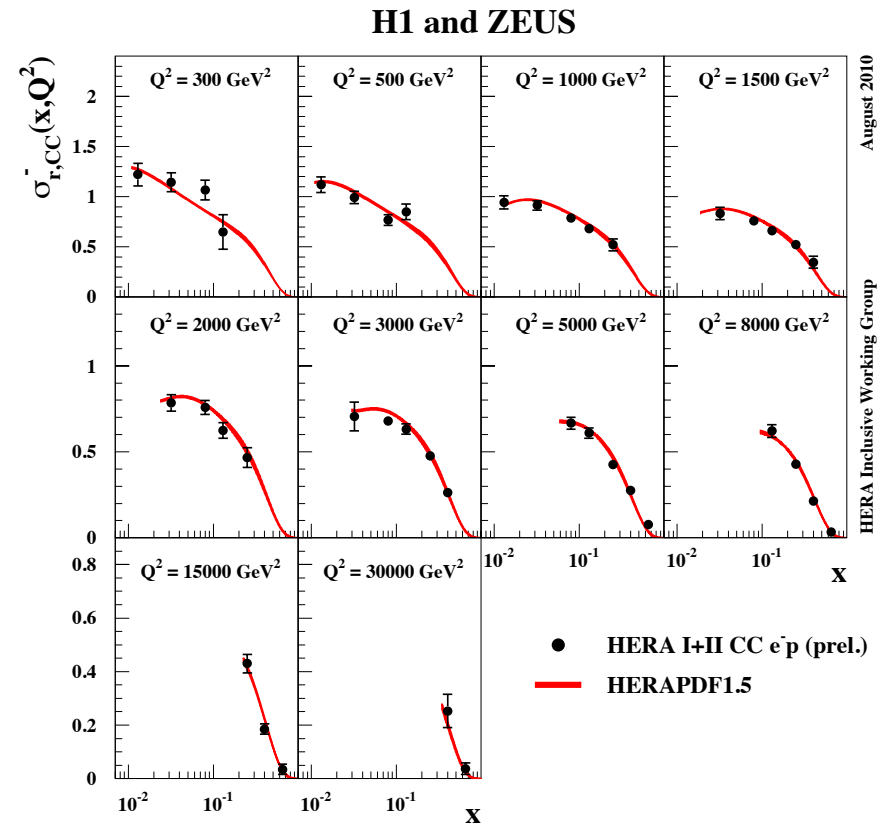### HERA-I + HERA-II combined results

New HERA-II measurements: increased precision at high-Q^2

HERA-II High-Q^2 data: CC e$^-$p

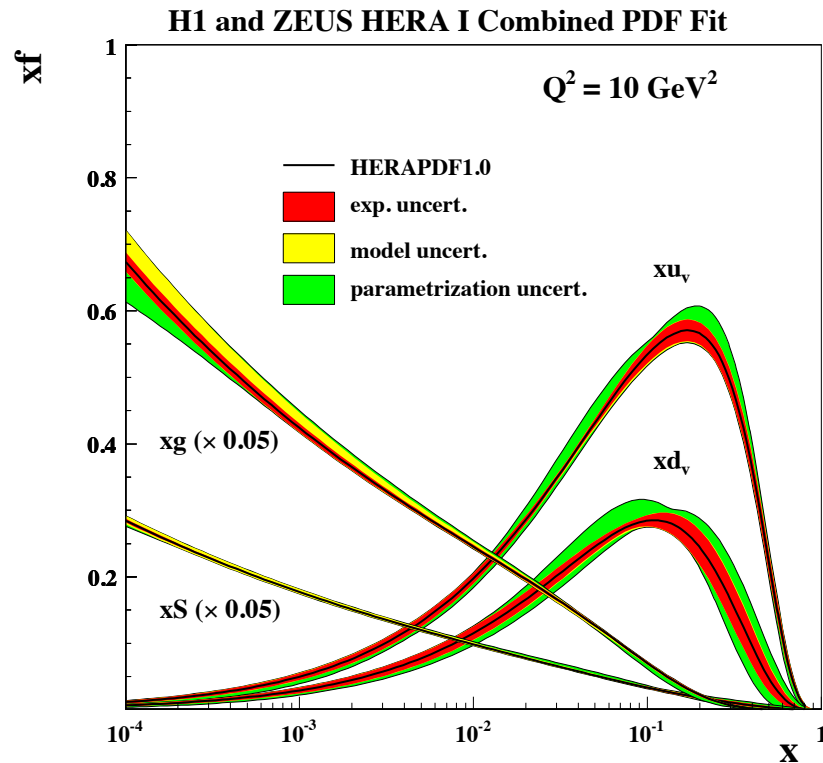## HERA-I combined results

HERA-I + HERA-II combined results
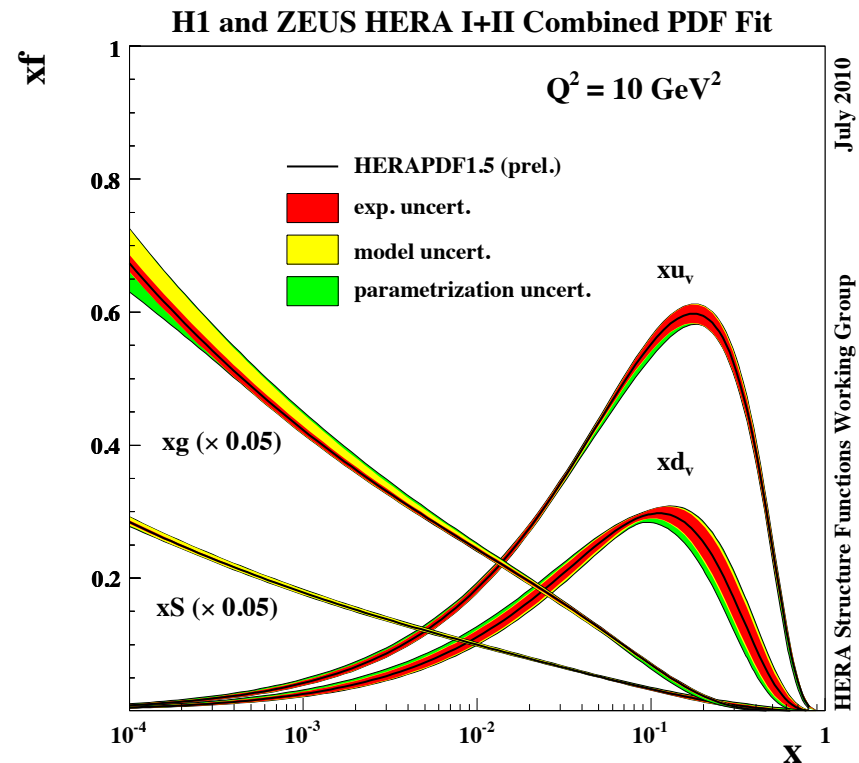

New HERA-II measurements: increased precision at high-Q^2

HERAPDF1.0 vs HERAPDF1.5

HERA-I / HERAPDF1.0   HERA-I+II / HERAPDF1.5

Impact on valence quarks: much better constrained at mid and high-x

Summary

HERA remains our main source of information on proton structure

Recent combined results of the H1 and ZEUS Collaborations have allowed to determine proton's PDFs with an unprecedented precision

Most of the improvements in the understanding of the PDFs, described here, are very relevant for the physics program of the LHC

Many results still to come (NNLO PDFs, new DGLAP analyses based on the full HERA-II data samples and new heavy flavour results).
Stay tuned!

For additional information and results please refer to:
https://www.desy.de/h1zeus/combined_results/