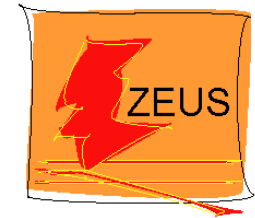# HERA Results on proton's PDFs

Enrico Tassi

(Università della Calabria and INFN)

On Behalf of the H1 and ZEUS Collaborations

Hadron Collider Physics Symposium 2012

Kyoto - November 10-15, 2012

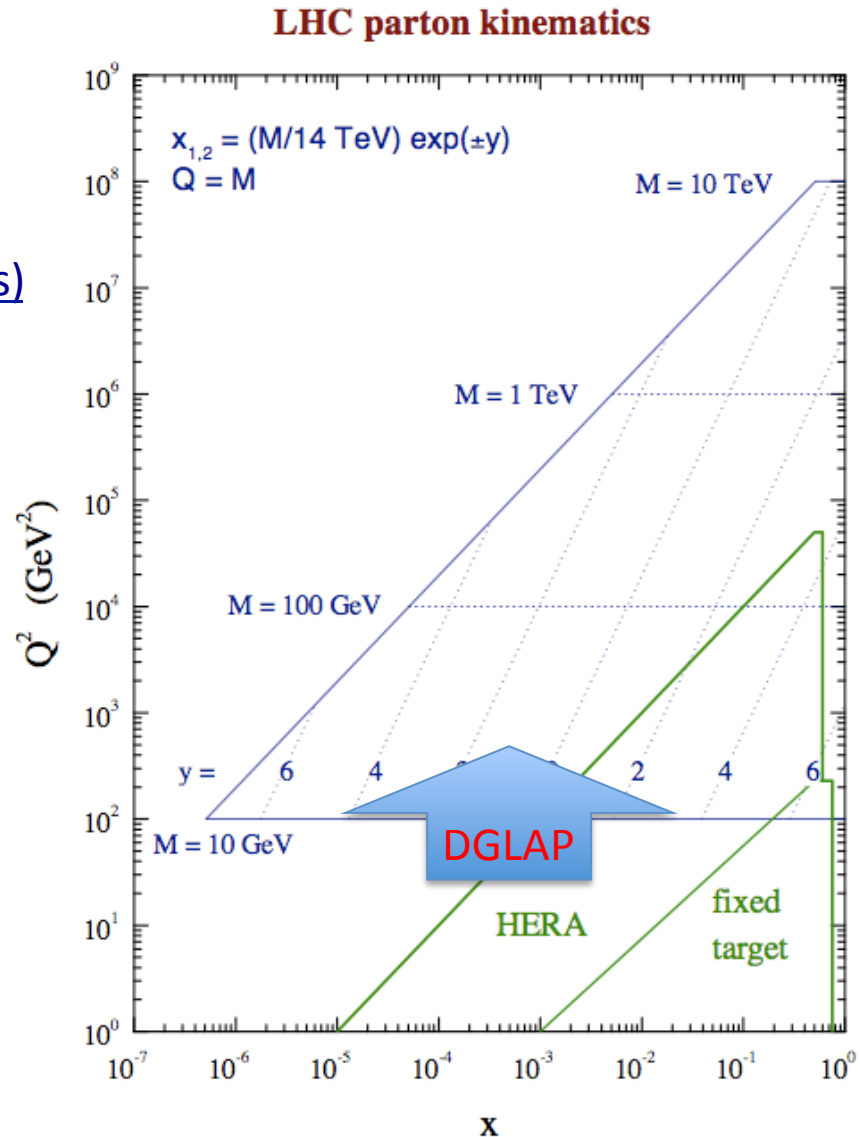# HERA and the Structure of the Proton

HERA data are our main source of knowledge on proton structure:
➔ proton's parton distribution functions (PDFs)

A very precise knowledge of PDFs is crucial to carry out the LHC Physics Program:
- Very stringent tests of the Standard Model
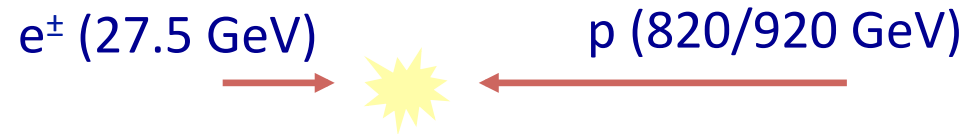- Searches of Physics Beyond the SM (need to control QCD Background)

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

LHC parton kinematics

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

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)

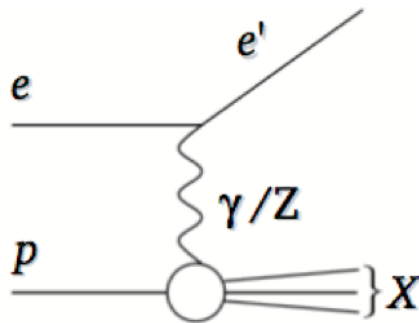**HERA-I (1992-2000)**
L ~ 130 pb^{-1}/experiment
Mostly e$^+$p

HERA-II (2003-2007)
L~360 pb^{-1}/experiment
Similar amounts of e$^+$p and e$^-$p

Long. polarized lepton beams (P~0.35)
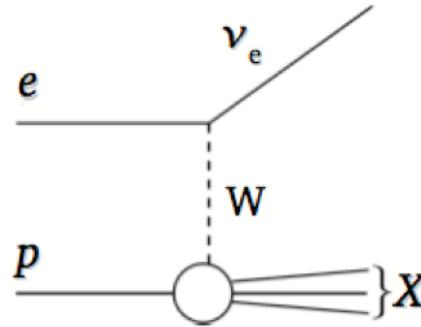Last months: Runs at reduced √s for F_L

DIS processes and cross sections

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

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

Kinematic variables:

- Virtuality exchanged boson

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

- Bjorken scaling variable

$$x = \frac{Q^2}{2p \cdot q}$$
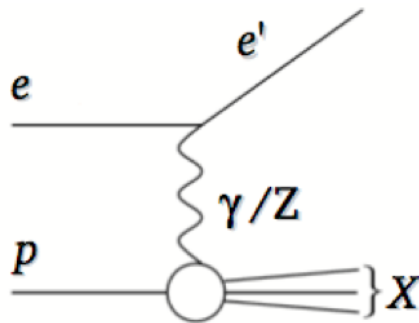
Double differential and "reduced" cross sections:

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

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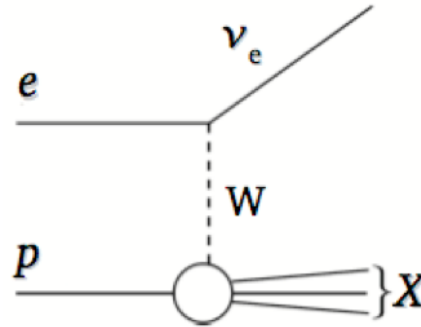
with $\quad Y_{\pm} = 1 \pm (1 - y)^2$

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

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

Structure Functions, PDFs and DGLAP evolution equations:

$$x^{-1} F_2(x, Q^2) = \sum_{i=q,g} \int_x^1 \frac{d\xi}{\xi} C_{2,i}\left(\frac{x}{\xi}, \alpha_s(\mu^2), \frac{\mu^2}{Q^2}\right) f_i(\xi, \mu^2)$$

$$\frac{d}{d\ln\mu^2} f_i(\xi, \mu^2) = \sum_k \left[P_{ik}(\alpha_s(\mu^2) \otimes f_k(\mu^2)) \right](\xi)$$

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

  - **HERA-I and HERA-II (Prel)+ jet data**:
    - ➔ Strong coupling and gluon density

  Preliminary

  - **HERA-I + charm data**:
    - ➔ Constraints on the charm mass and study of different heavy quarks schemes

    arXiv:1211.1182 (➔EPJC) - new for HCP2012

- **Final results of the H1 an ZEUS collaborations with HERA-II data**
  - **H1 NC and CC $e^{\pm}p$ high Q^2 Cross Sections and new QCD analysis**

    arXiv:1206.7007 (➔JHEP)

  - **ZEUS NC e^+p high Q^2 cross sections**

    arXiv:1208.6138 (➔EPJC)

HERAPDFs

HERAPDF: only HERA data
 - uses consistent data with very well understood systematics and correlations
 - no need for nuclear corrections etc

Overview of HERAPDF sets:

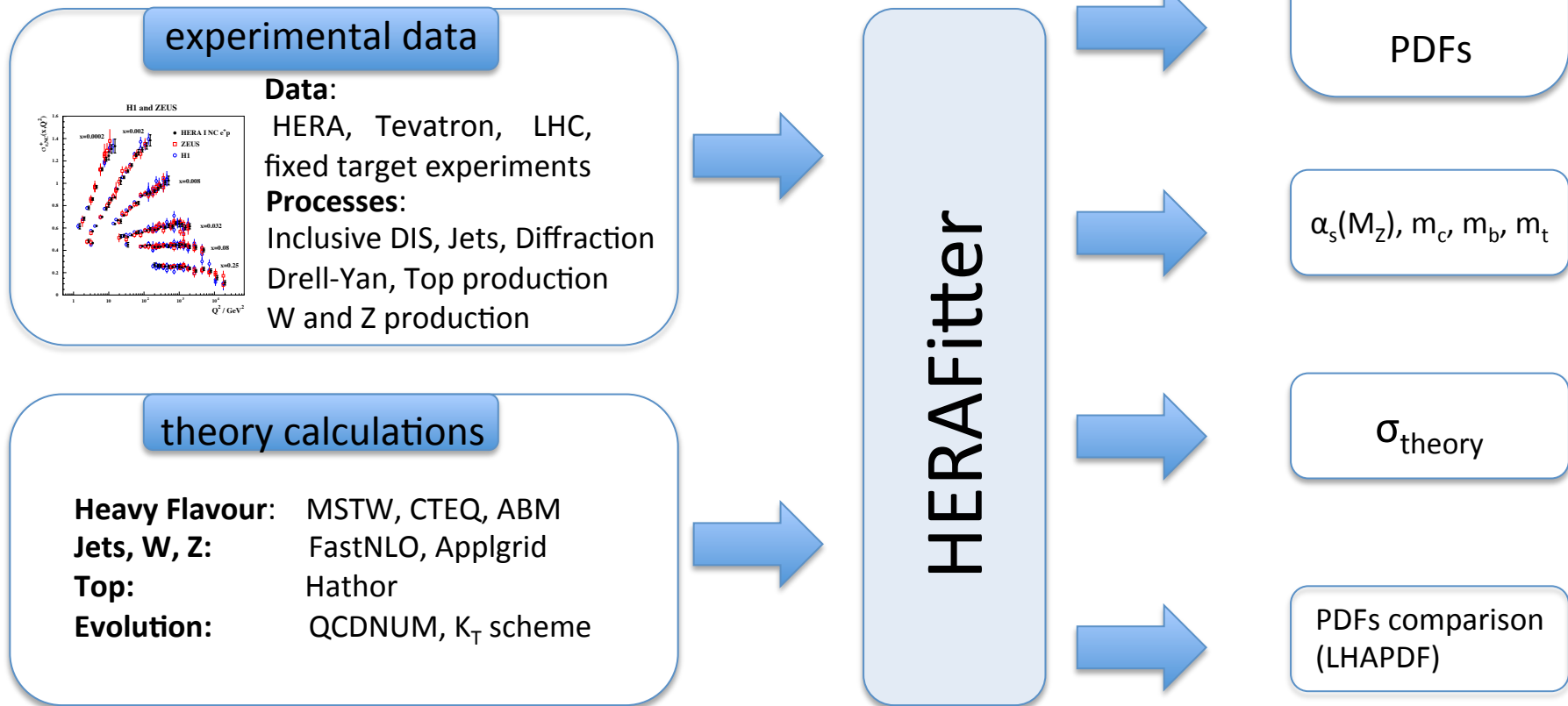| Data	PDF Set
H1+ZEUS NC,CC - HERA I	HERAPDF1.0 (NLO,NNLO)
H1+ZEUS NC,CC - HERA I +II (part)	HERAPDF1.5 (NLO,NNLO)
NC,CC HERA I + II (part) + jets	HERAPDF1.6 (NLO)
NC,CC HERA I + charm	HERAPDF1.0 + charm (NLO)
Planned: Full HERA data set	HERAPDF2.0 (NLO, NNLO)

Latest DGLAP analyses use the **HERAFitter** package
  - Open source QCD fitting tool to determine PDFs
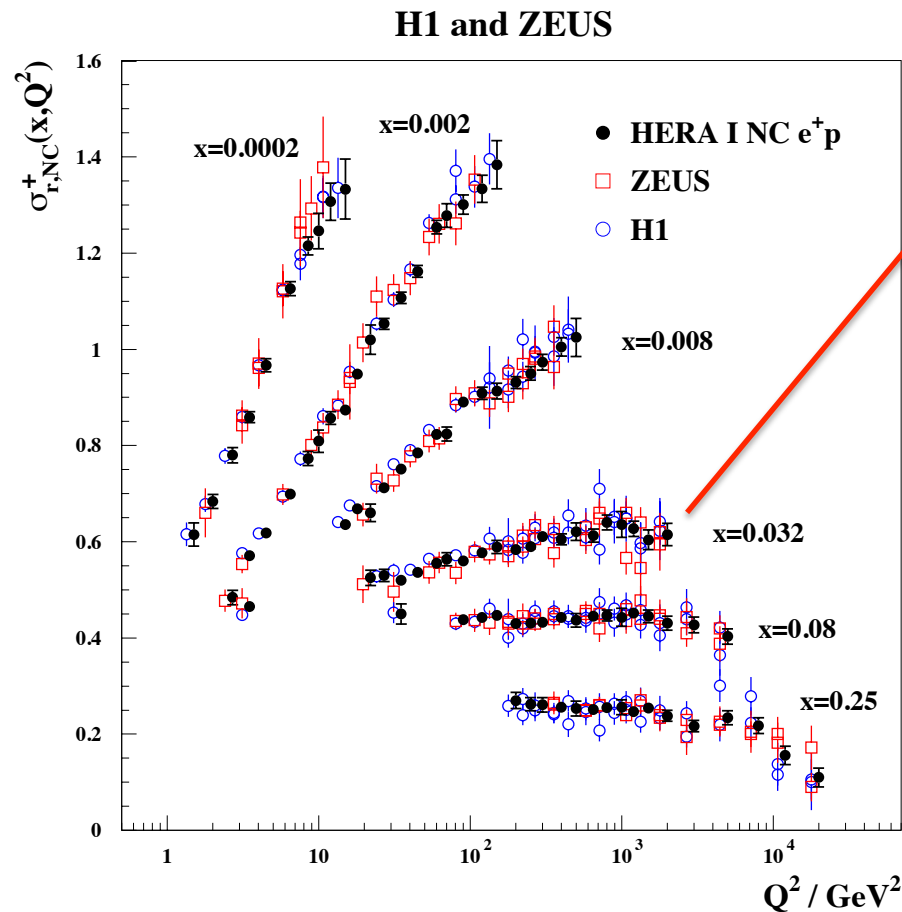 - Developers: H1,ZEUS, ATLAS and CMS (see http://projects.hepforge.org/herafitter)

HERAFitter

Modular Structure:

experimental data

Data:
HERA, Tevatron, LHC, fixed target experiments
Processes:
Inclusive DIS, Jets, Diffraction
Drell-Yan, Top production
W and Z production

theory calculations

Heavy Flavour: MSTW, CTEQ, ABM
Jets, W, Z: FastNLO, Applgrid
Top: Hathor
Evolution: QCDNUM, K_T scheme

HERAFitter

PDFs

$\alpha_s(M_Z), m_c, m_b, m_t$

σ_{theory}

PDFs comparison (LHAPDF)

Active participation and support of many theory groups
Global benchmarking platform for PDFs and QCD in general
First ATLAS analysis based on HERAFitter (s-quark density) recently published

Combination of HERA I data

H1 and ZEUS

- 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
  - 1-2% total uncert. in the low- mid-Q^2 region

JHEP 1001:109(2010)

Combination of HERA I data

DGLAP Analysis of HERA-I data: HERAPDF 1.0

H1 and ZEUS

$Q^2 = 10$ GeV^2

HERAPDF1.0
exp. uncert.
model uncert.
parametrization uncert.

$xg \ (\times \ 0.05)$

xu_v

$xS \ (\times \ 0.05)$

xd_v

xf

X

- NLO DGLAP analysis based only on the HERA-I, fully consistent, combined dataset:
  - no need for heavy target/deuterium corrections or strong isospin assumptions
  - χ^2/ndof = 574/582

- Massive treatment for heavy flavours (RT-VFNS)

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

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

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

HERAPDF1.0
exp. uncert.
model uncert.
param uncert.

xu_{sea}
xd_{sea}
xs_{sea}
xc_{sea}
xb_{sea}

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]

Parameterization uncertainty:

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

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

At the scale Q²=10 000 GeV² (relevant to LHC)
the sea and gluon densities are known at the % level for x ≤ 10^{-1}

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

HERAPDF1.0 vs HERAPDF1.5

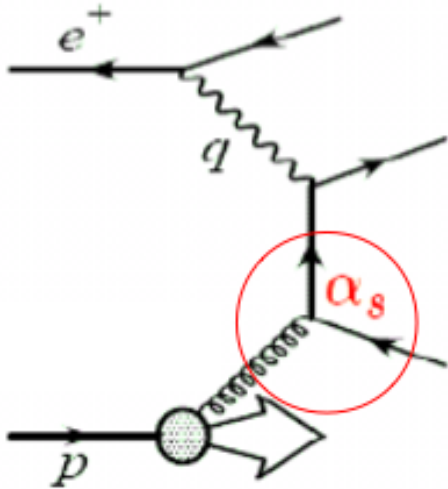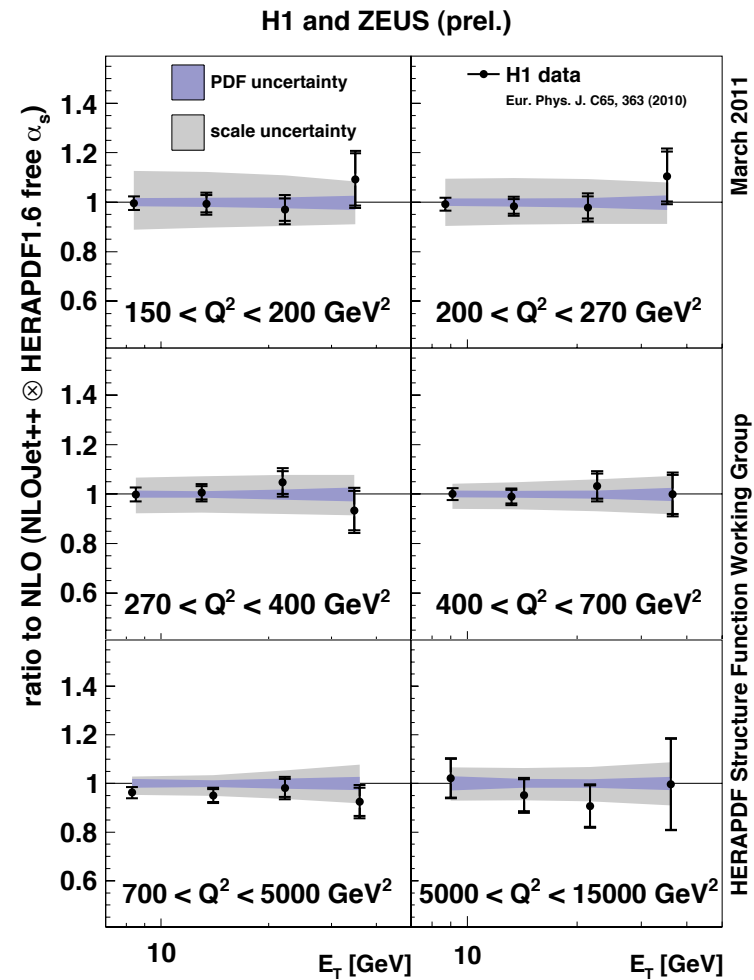**HERA-I / HERAPDF1.0**

HERA-I+II / HERAPDF1.5

Impact on valence quarks: much better constrained at mid and high-x
Final analysis with full HERA data sets on-going…
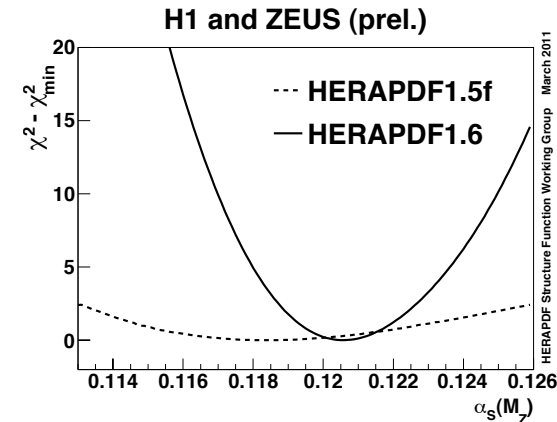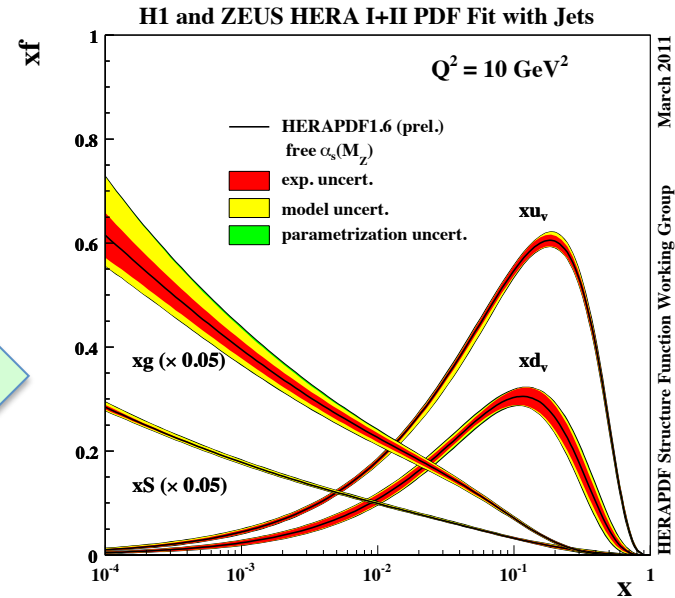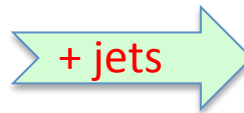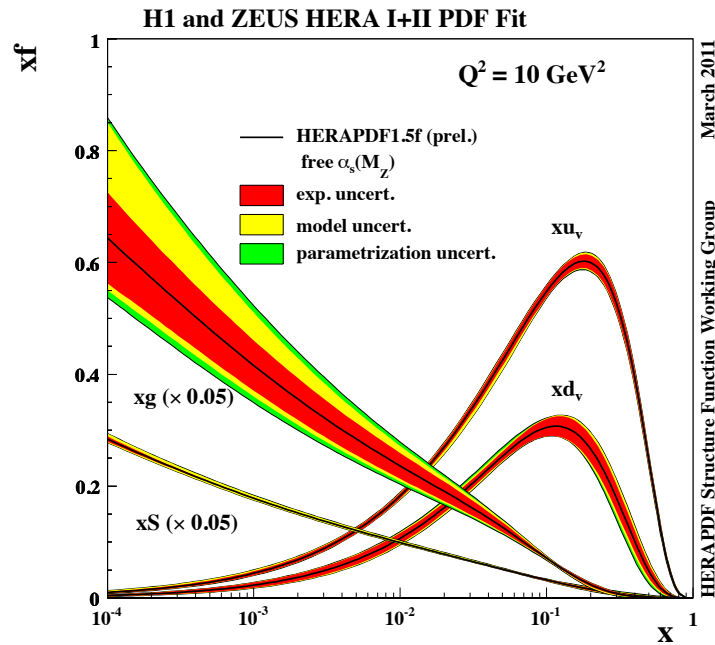
Inclusion of jets: HERAPDF1.6

HERAPDF1.6:   CC,NC HERA I + II (Prel.) +
4 inclusive jet measurements from H1 and ZEUS

Direct sensitivity to gluon and strong coupling constant
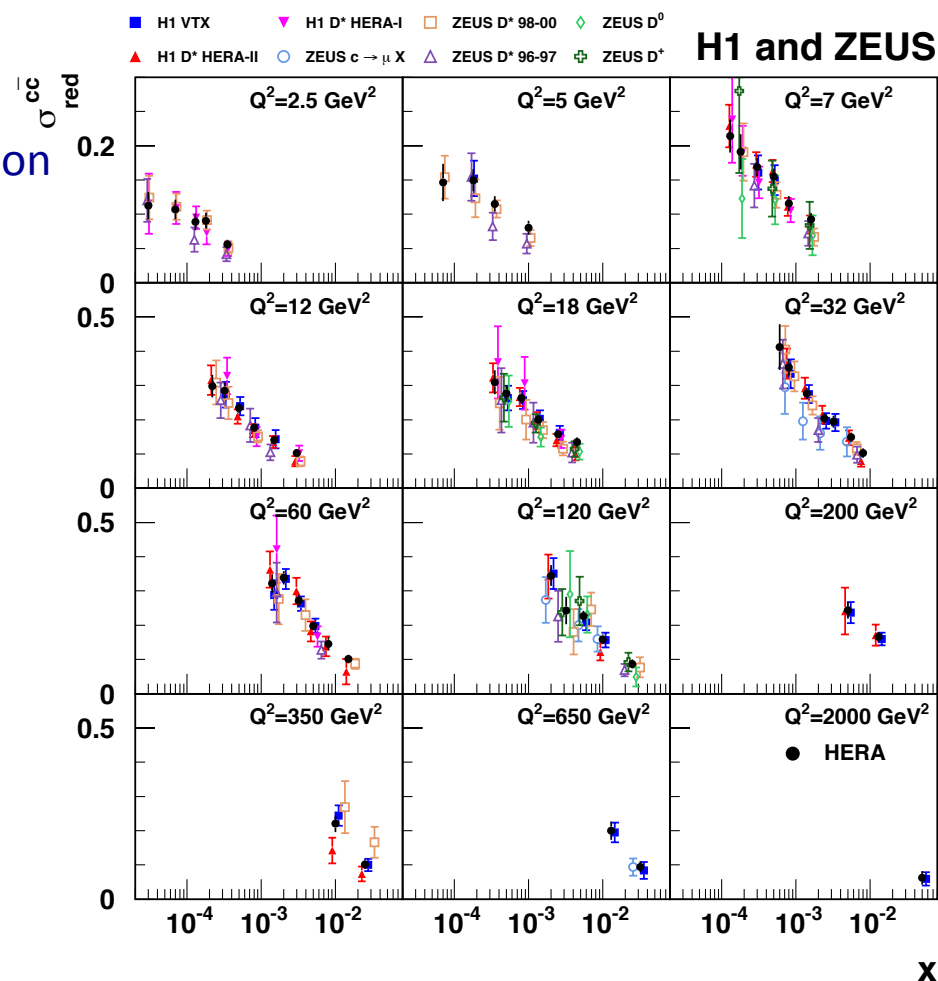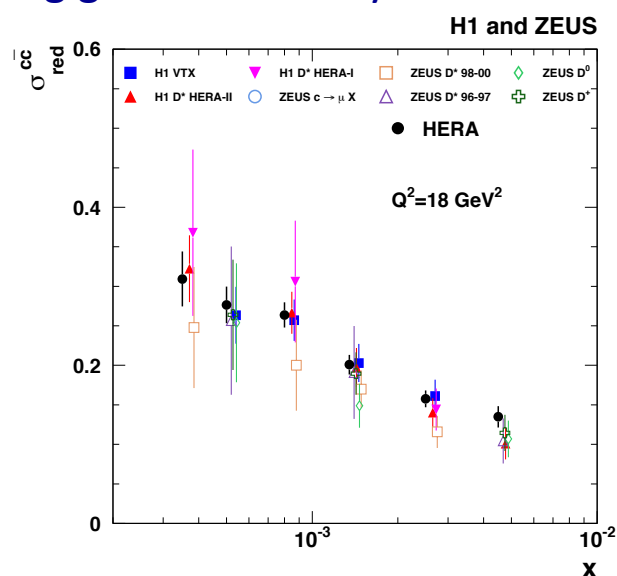
Inclusion of jets: HERAPDF1.6

+ jets

HERA Jet data allow to constrain simultaneously α_s and gluon

$$\alpha_s(M_Z) = 0.1202 \pm 0.0013(\text{exp}) \pm 0.0007(\text{mod}) \pm 0.0012(\text{had})^{+0.0045}_{-0.0036}(\text{th})$$

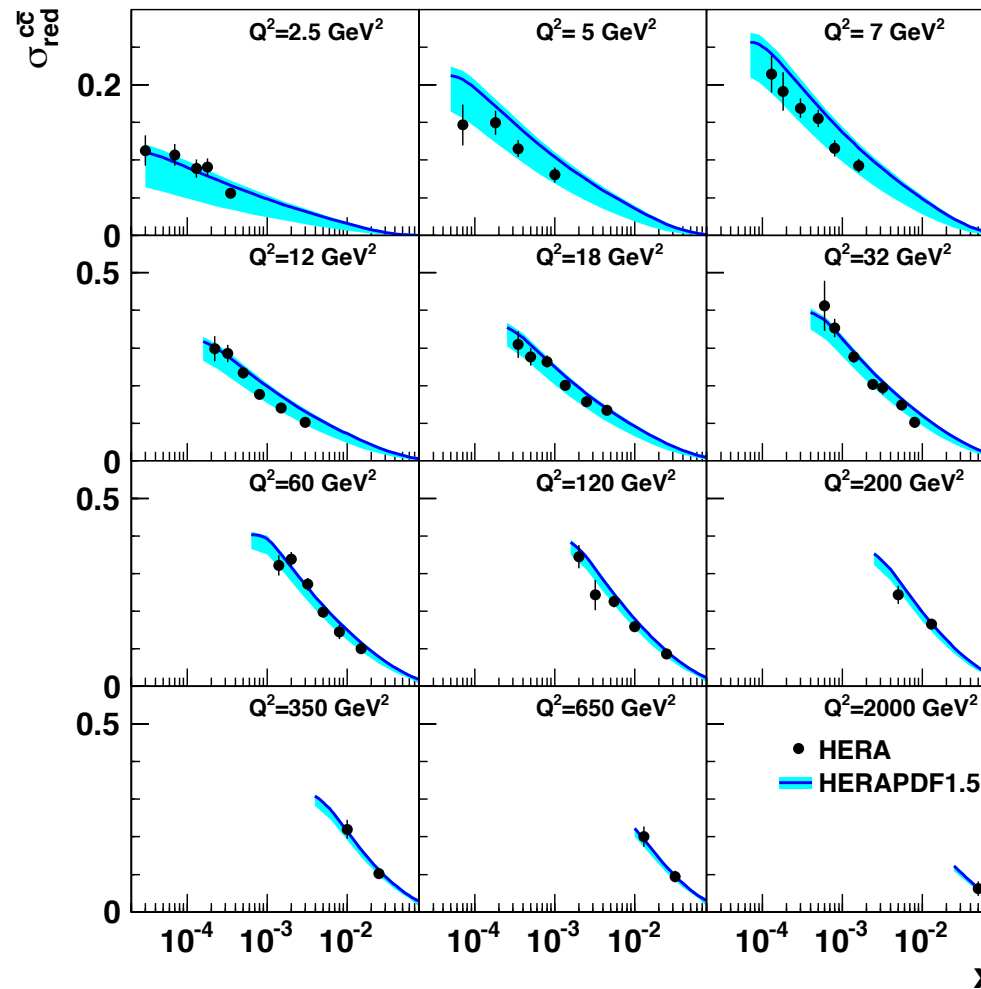# Inclusion of Charm data

Combine H1 and ZEUS charm data:
(accuracy 7-10%)

Heavy Quarks (HQ) treatment in DGLAP evolution equations is a very important topic in QCD.
Fixed Flavour Number Scheme (FFNS) vs
General Mass Variable Flavour Number Scheme(GM-VFNS).

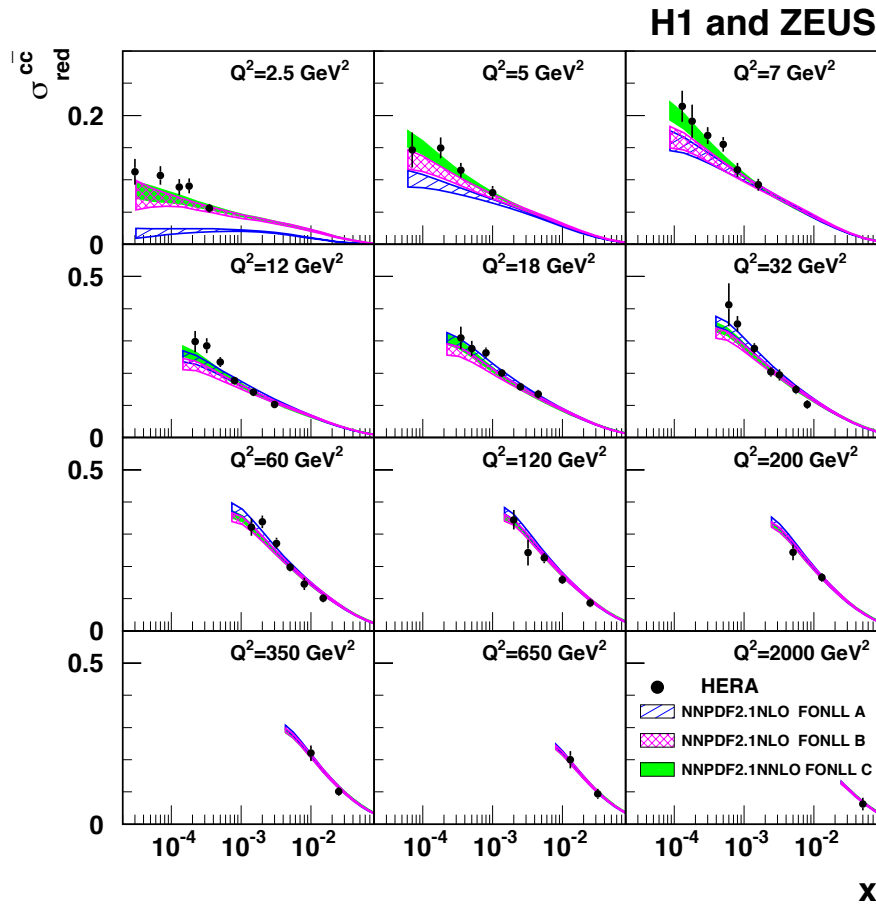New HERA combined charm data natural testing ground to study different HQ schemes.

arXiv:1211.1182 (➔EPJC)

Inclusion of Charm data
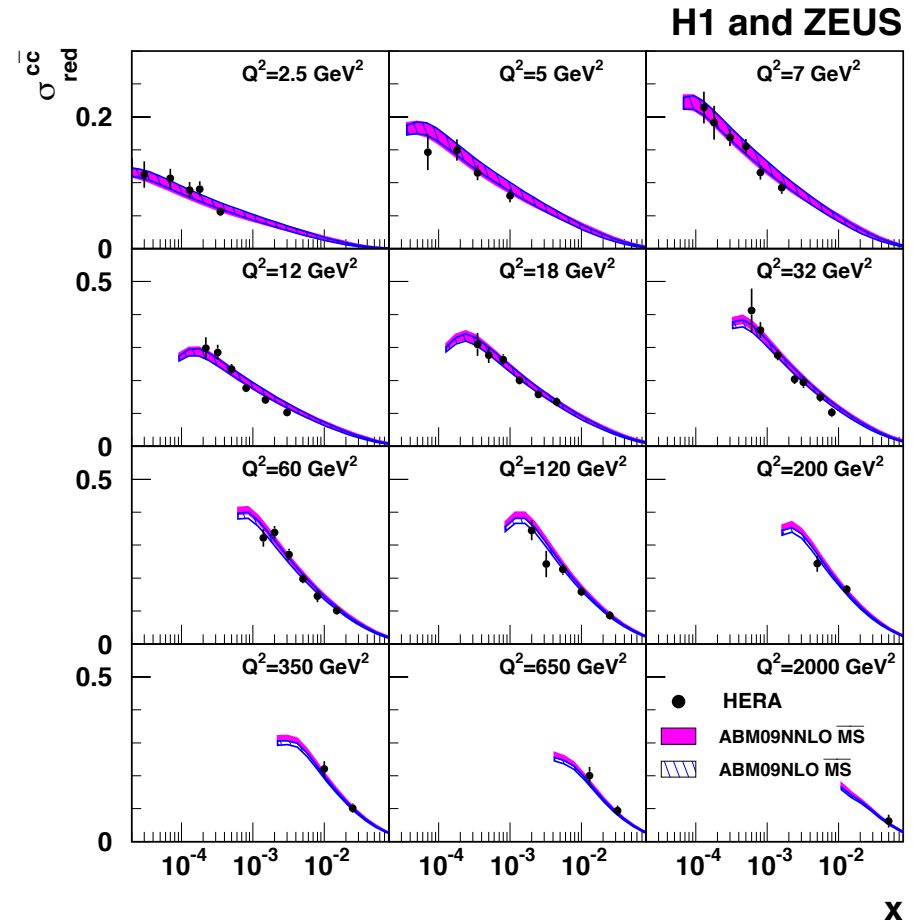

Reasonable agreement with QCD prediction, based on HERAPDF1.5, when accounting for uncertainty on m_c. Uncertainty band: $1.35 < m_c < 1.65$ GeV.
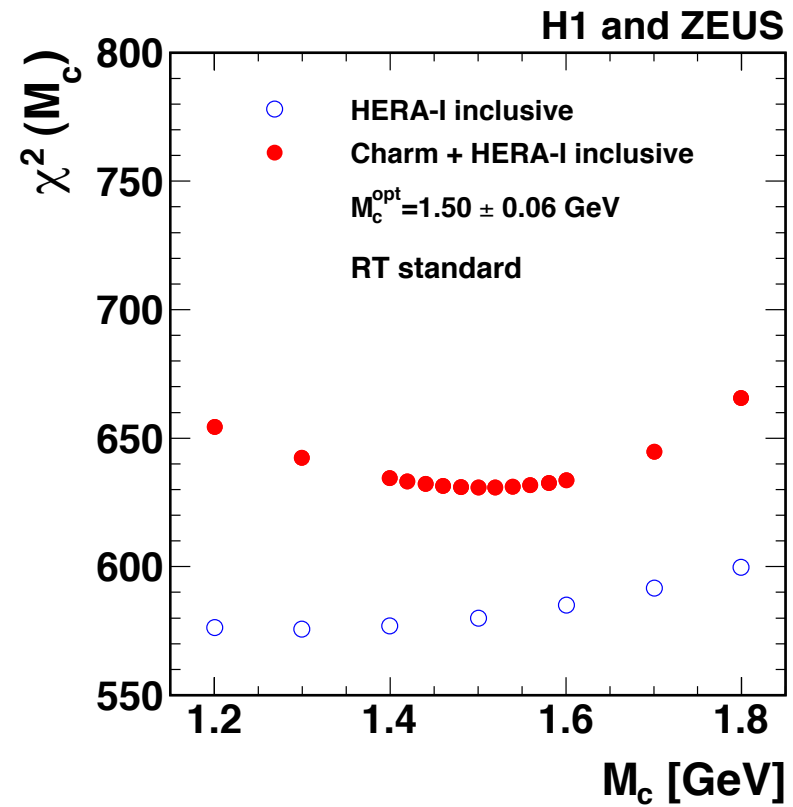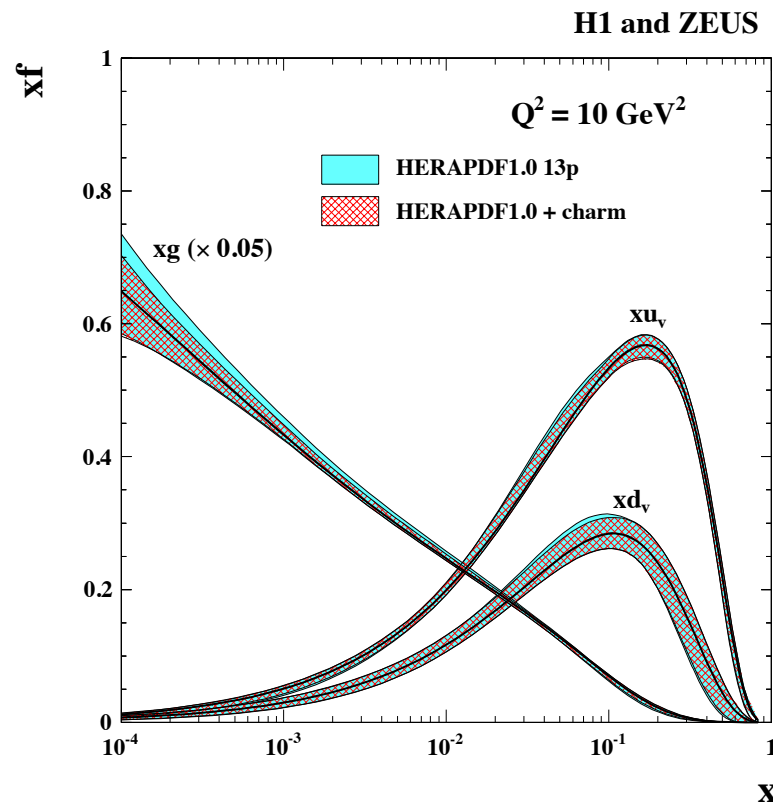
Inclusion of Charm data

NNPDF2.1 (NLO and approx. NNLO)
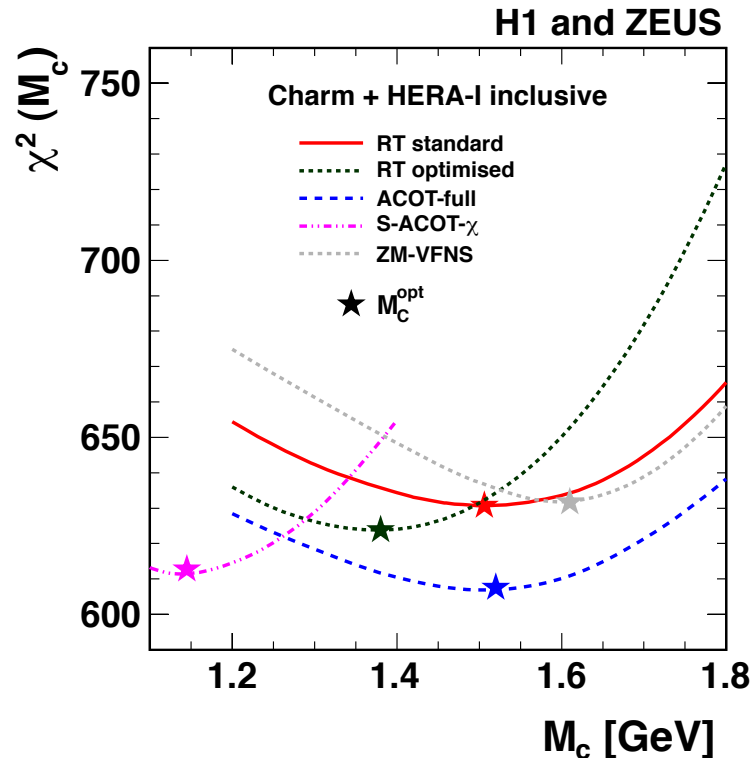GM-VFNS

ABM09 (NLO and approx. NNLO)
FFNS

Inclusion of Charm data

...does not change PDF significantly, but increases sensitivity to charm mass
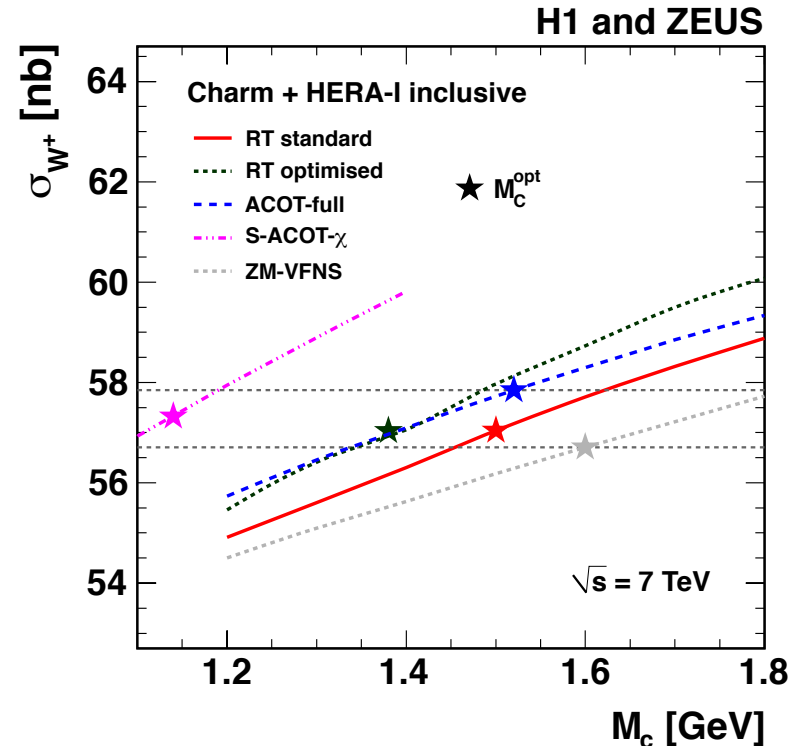
Charm, VFNS schemes and W predictions at LHC

W⁺ cross section @ LHC

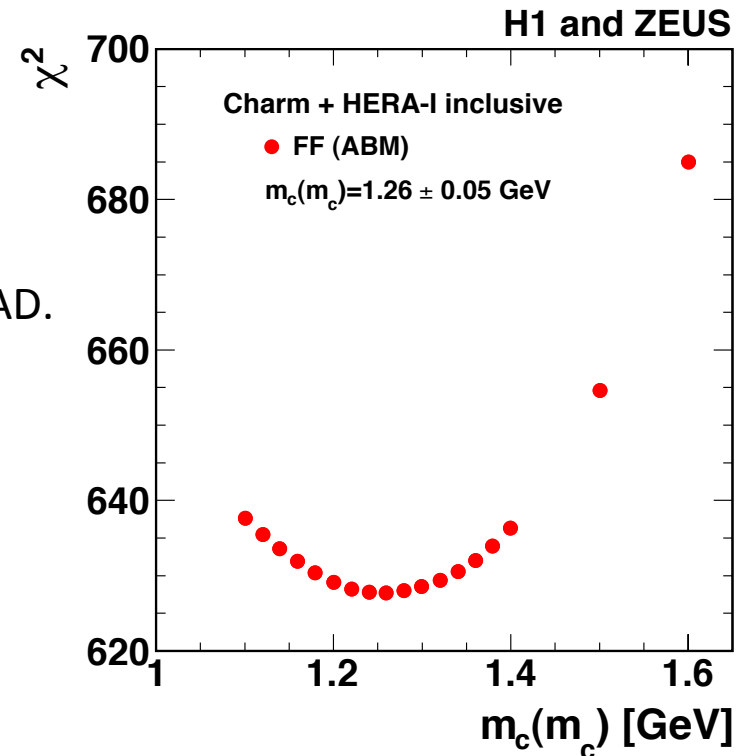Different "optimal" effective masses for different GM-VFNS yield very similar fits

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)

Determination of the Running Charm Mass

An NLO QCD analysis is performed in the FFNS approach of the ABM group to determine the $\overline{MS}$ running charm quark mass $m_c(m_c)$.
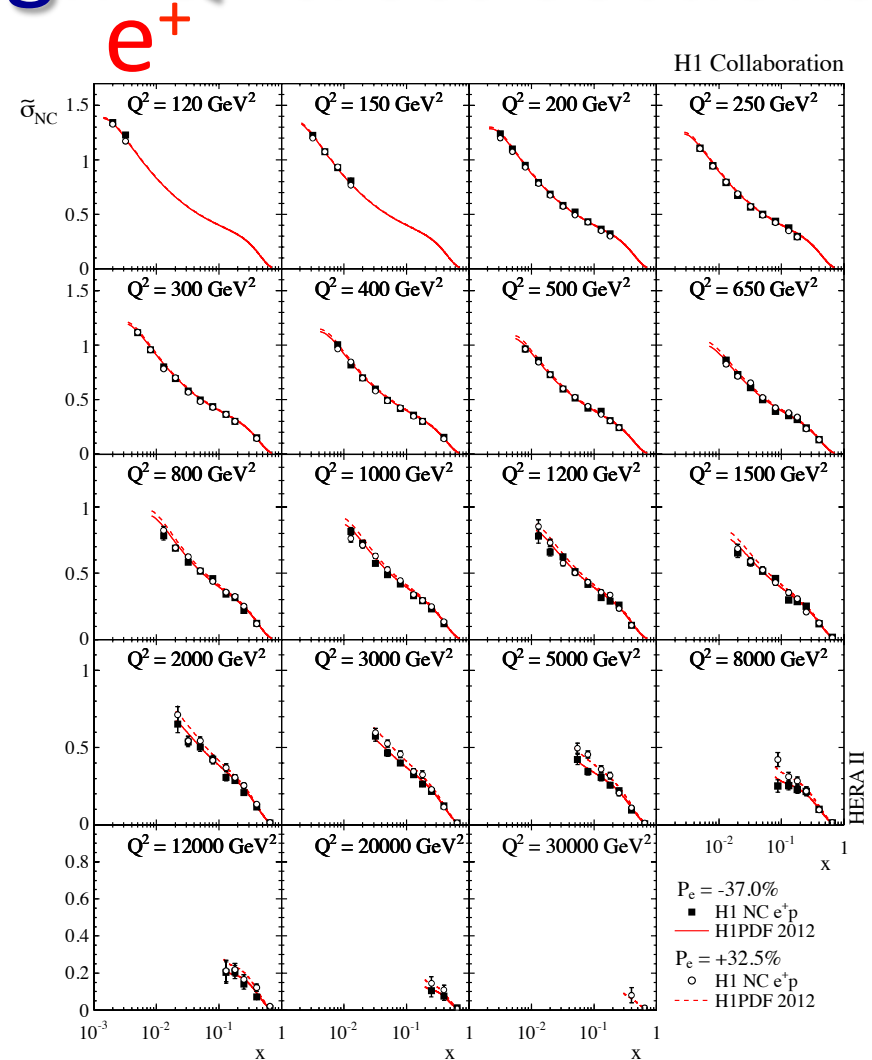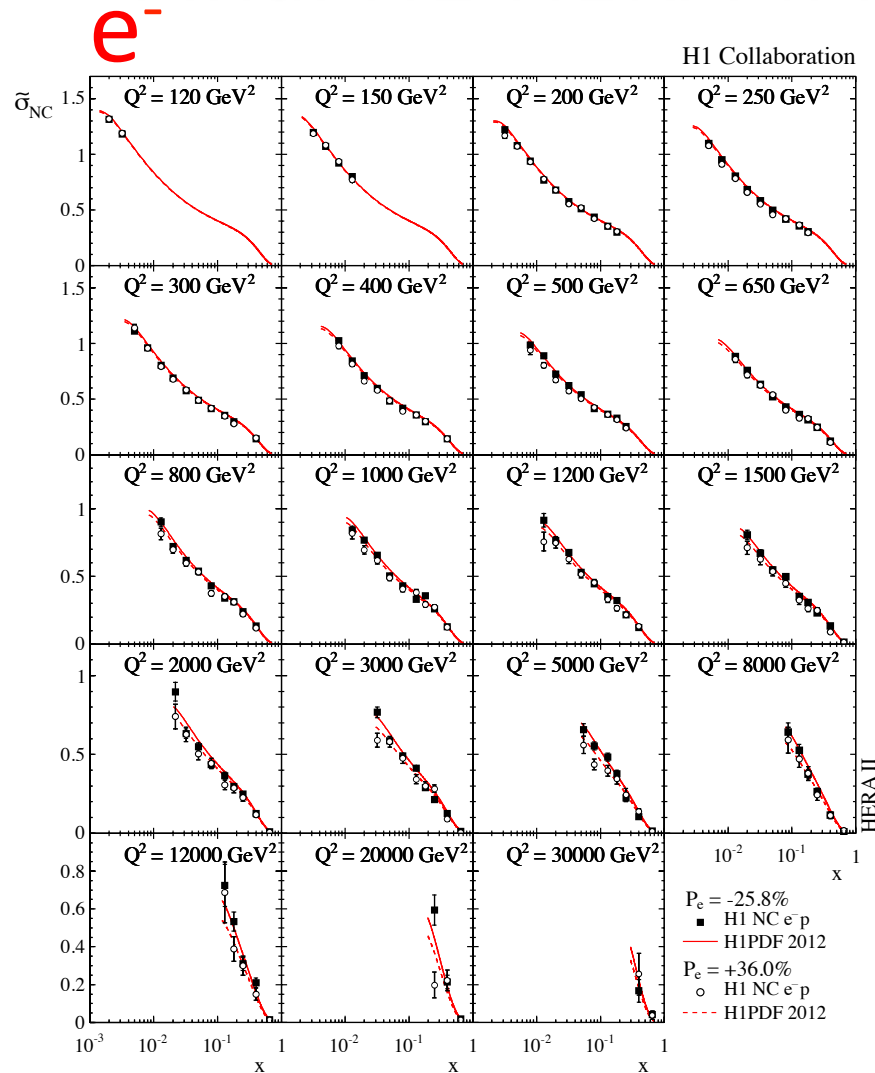
Coefficient functions as implemented in OPENQCDRAD.

Obtained result is compatible with world average
$$m_c(m_c) = 1.275 \pm 0.025$$
based on lattice calculations and measurement of time-like processes.

$$m_c(m_c) = 1.26 \pm 0.05_{\mathrm{exp}} \pm 0.03_{\mathrm{mod}} \pm 0.02_{\mathrm{param}} \pm 0.02_{\alpha_s} \,\mathrm{GeV}$$
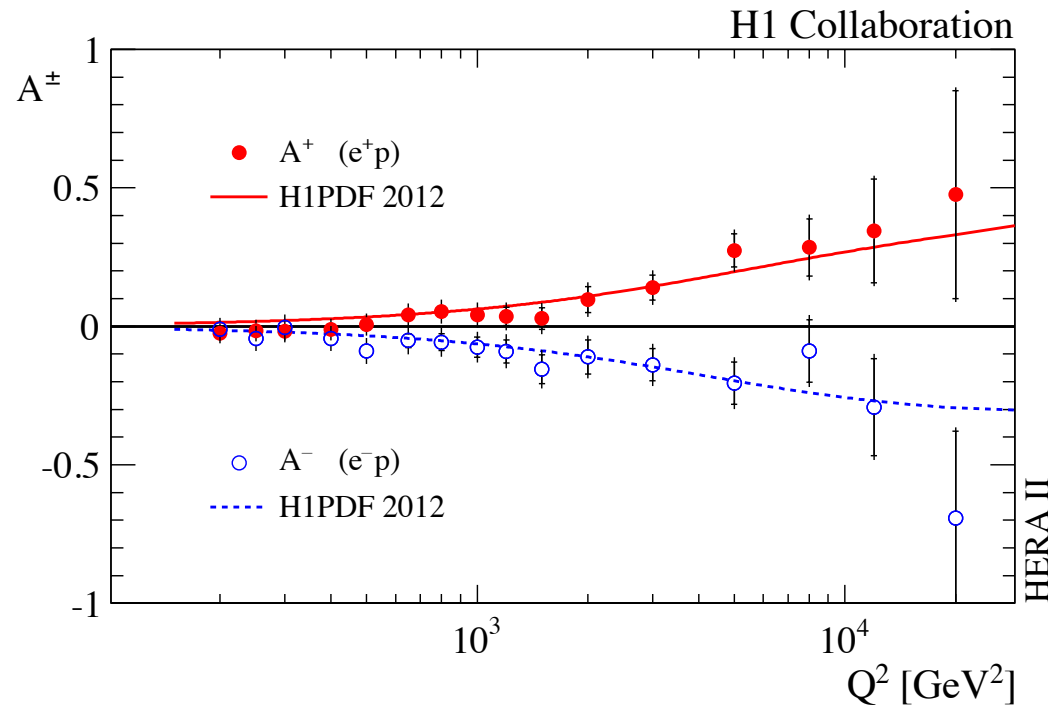
Final H1 HERA-II High-Q^2 cross sections

- Show here only NC $e^\pm p$ Reduced Cross Sections
- Polarized Cross sections well described by SM predictions (H1PDF 2012)

arXiv:1206.7007 (→JHEP)
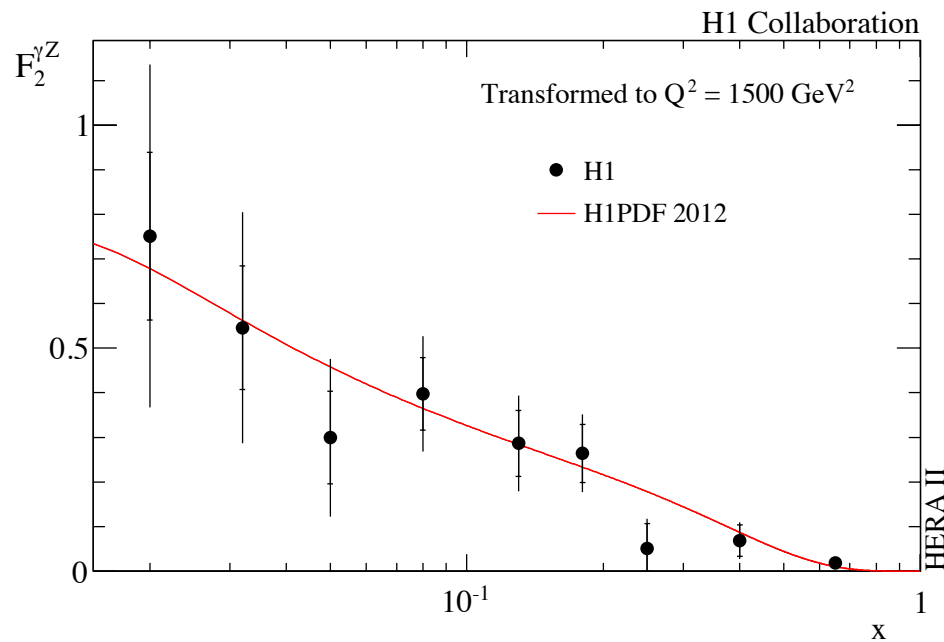
NC Polarization Asymmetry

$$A^{\pm} = \frac{2}{P_L^{\pm} - P_R^{\pm}} \cdot \frac{\sigma^{\pm}(P_L^{\pm}) - \sigma^{\pm}(P_R^{\pm})}{\sigma^{\pm}(P_L^{\pm}) + \sigma^{\pm}(P_R^{\pm})}$$

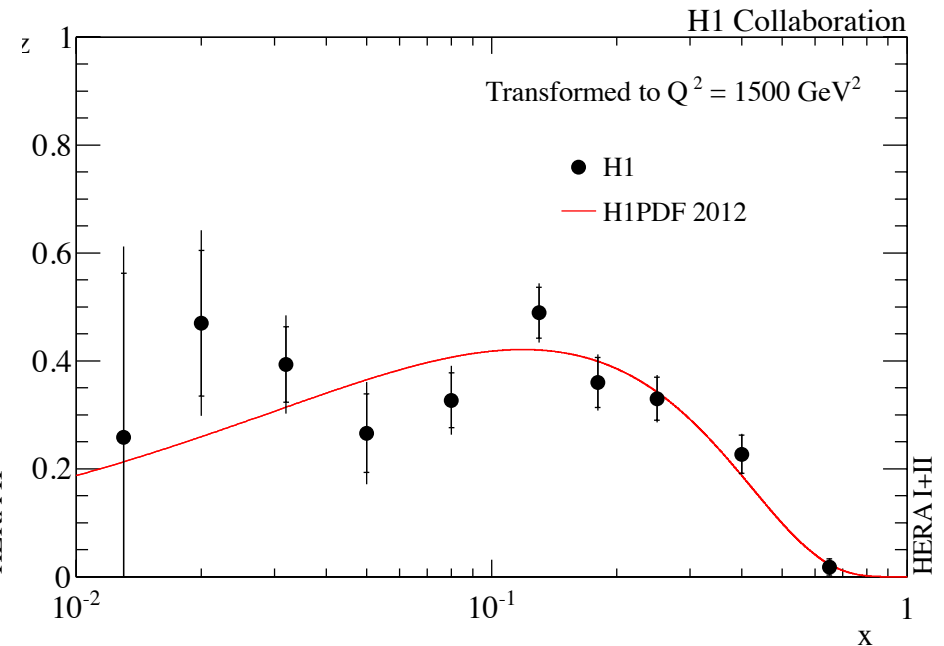Direct measure of Parity violation effects in NC DIS

Structure Functions $F_2^{\gamma Z}$, $F_3^{\gamma Z}$

First measurement of $F_2^{\gamma Z}$
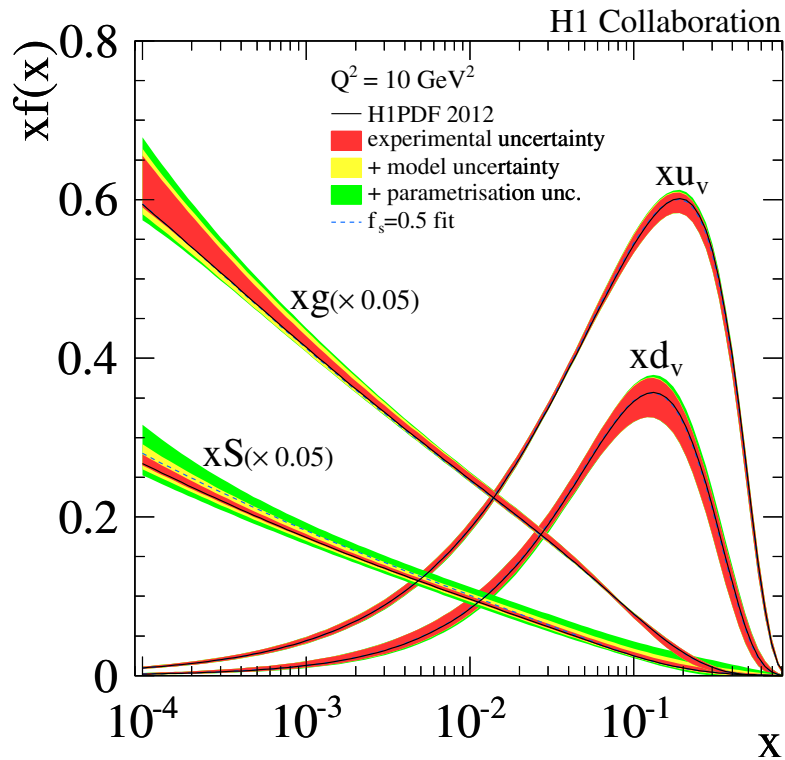
Improved measurement of $F_3^{\gamma Z}$

$$F_2^{\gamma Z} \sim q + \bar{q}$$

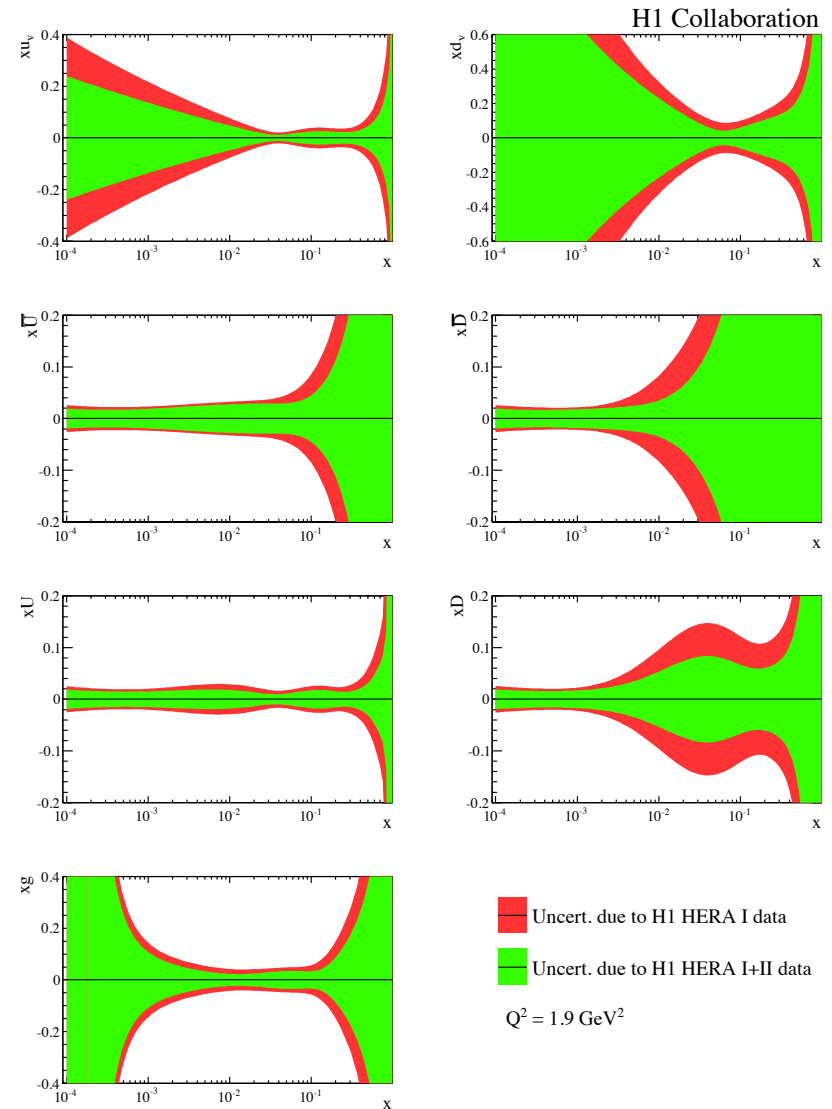$$xF_3^{\gamma Z} \sim xq_v$$

H1PDF 2012

- HERAFitter
- 5 sets of PDFs (with 13 free parameters)

Reduced uncertainties in particular for down-type quarks (xD)

Final ZEUS HERA-II NC e⁺p cross sections

ZEUS

ZEUS

- Very pure signal, good agreement with MC expectations
- Reduced Cross sections (corrected to P=0) well described by SM predictions (HERAPDF1.5)

arXiv:1208.6138 (→EPJC)   27

Final ZEUS HERA-II NC e⁺p cross sections

- Improved determination of $F_3^{\gamma Z}$

- Parity violation demonstrated down to scale 10^{-18} m

Summary

HERA remains our main source of information on proton's structure
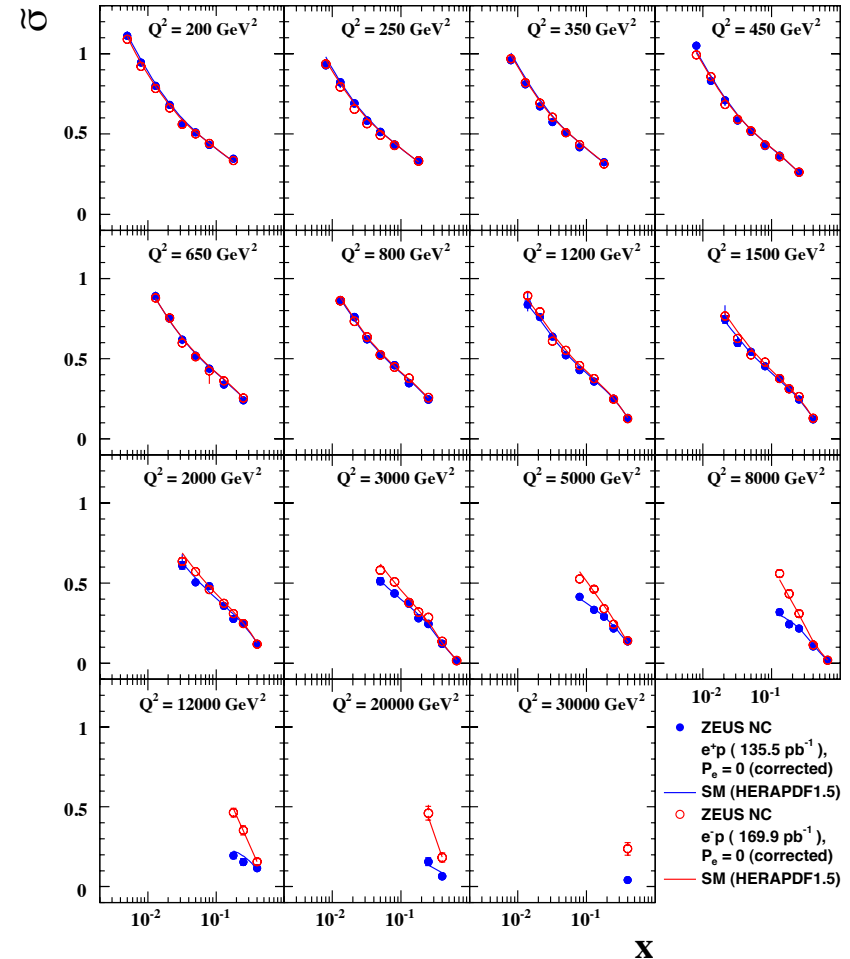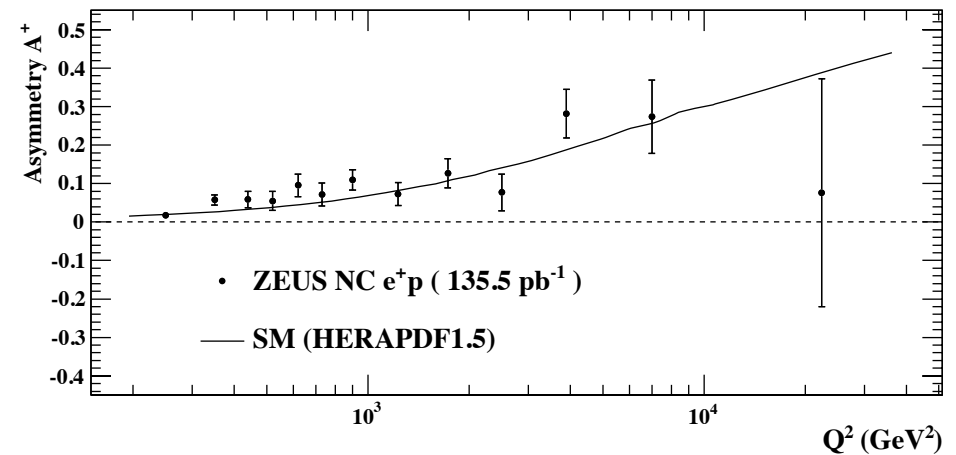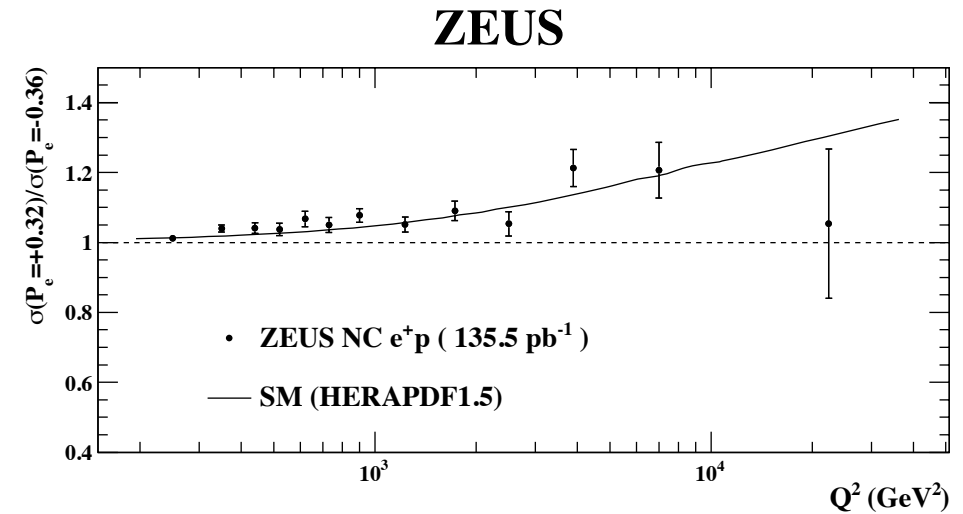
Recent combined results of the H1 and ZEUS Collaborations have allowed
to determine proton's PDFs with an unprecedented precision

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

Final High Q^2 NC and CC HERA II Cross sections are now published and
the final HERA combinations and QCD Analyses are being worked on.

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

Backup

Charm Theoretical Predictions

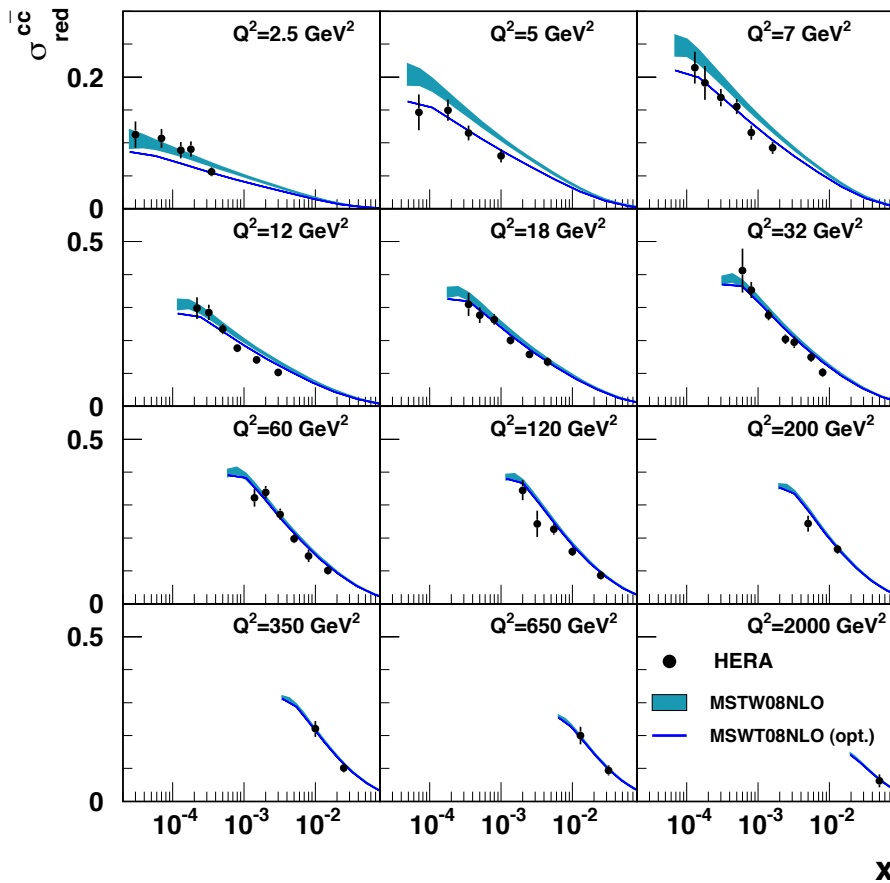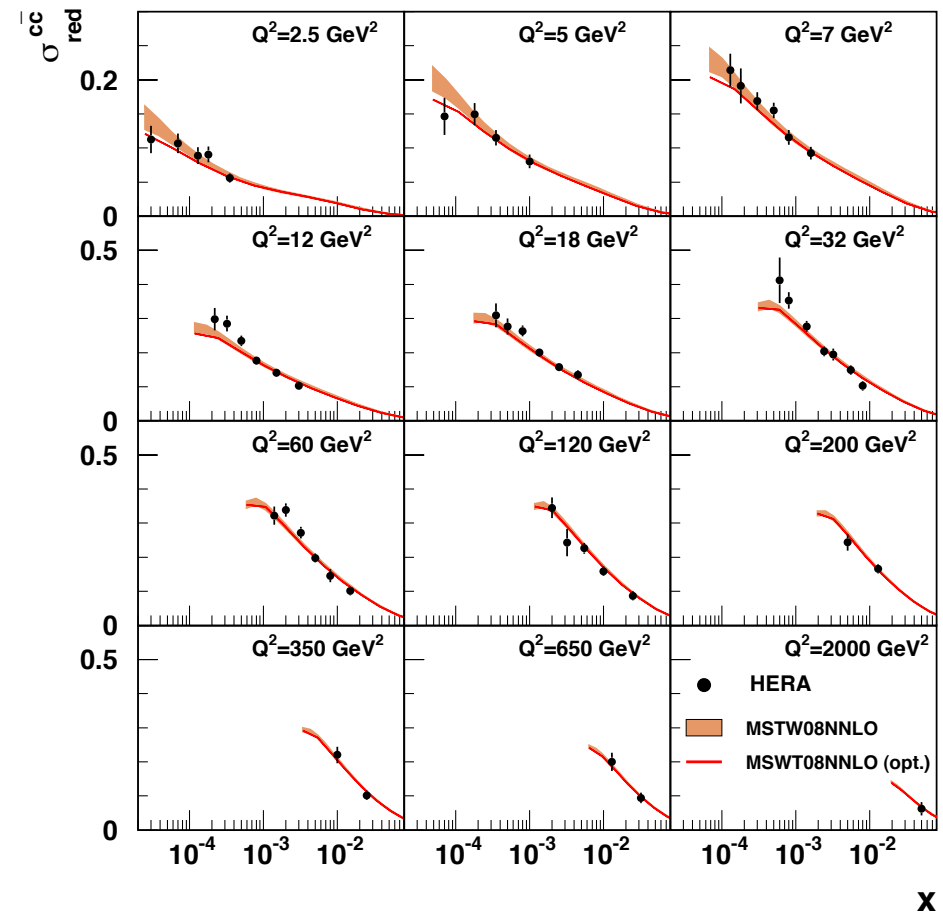| Theory	Scheme	Ref.	$F_{2(L)}$ def.	m_c [GeV]	Massive ($Q^2 \lesssim m_c^2$)	Massless ($Q^2 \gg m_c^2$)	$\alpha_s(m_Z)$ ($n_f = 5$)	Scale	Included charm data
MSTW08 NLO	RT standard	[28]	$F_{2(L)}^c$	1.4 (pole)	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s)$	0.12108	Q	[1,4–6,8,9,11]
MSTW08 NNLO					approx.-$\mathcal{O}(\alpha_s^3)$	$\mathcal{O}(\alpha_s^2)$	0.11707		
MSTW08 NLO (opt.)	RT optimised	[31]			$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s)$	0.12108		
MSTW08 NNLO (opt.)					approx.-$\mathcal{O}(\alpha_s^3)$	$\mathcal{O}(\alpha_s^2)$	0.11707		
HERAPDF1.5 NLO	RT standard	[55]	$F_{2(L)}^c$	1.4 (pole)	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s)$	0.1176	Q	HERA inclusive DIS only
NNPDF2.1 FONLL A	FONLL A	[30]	n.a.	$\sqrt{2}$	$\mathcal{O}(\alpha_s)$	$\mathcal{O}(\alpha_s)$	0.119	Q	[4–6,12,13,15,18]
NNPDF2.1 FONLL B	FONLL B		$F_{2(L)}^c$	$\sqrt{2}$ (pole)	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s)$			
NNPDF2.1 FONLL C	FONLL C		$F_{2(L)}^c$	$\sqrt{2}$ (pole)	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s^2)$			
CT10 NLO	S-ACOT-χ	[22]	n.a.	1.3	$\mathcal{O}(\alpha_s)$	$\mathcal{O}(\alpha_s)$	0.118	$\sqrt{Q^2 + m_c^2}$	[4–6,8,9]
CT10 NNLO (prel.)		[56]	$F_{2(L)}^{c\bar{c}}$	1.3 (pole)	$\mathcal{O}(\alpha_s^2)$	$\mathcal{O}(\alpha_s^2)$			
ABKM09 NLO	FFNS	[57]	$F_{2(L)}^{c\bar{c}}$	1.18 ($\overline{\text{MS}}$)	$\mathcal{O}(\alpha_s^2)$	-	0.1135	$\sqrt{Q^2 + 4m_c^2}$	for mass optimisation only
ABKM09 NNLO					approx.-$\mathcal{O}(\alpha_s^3)$	-			

MSTW08 Charm Predictions
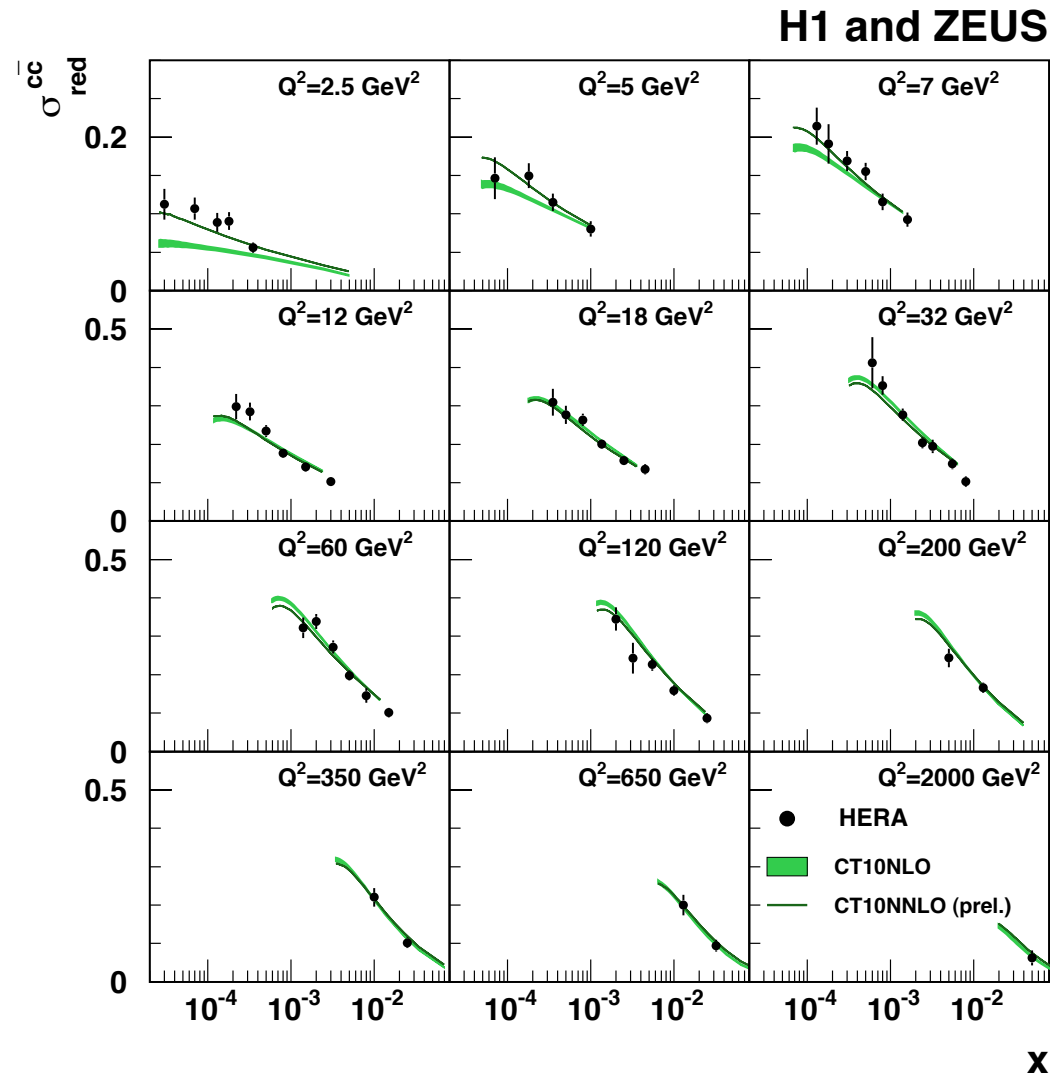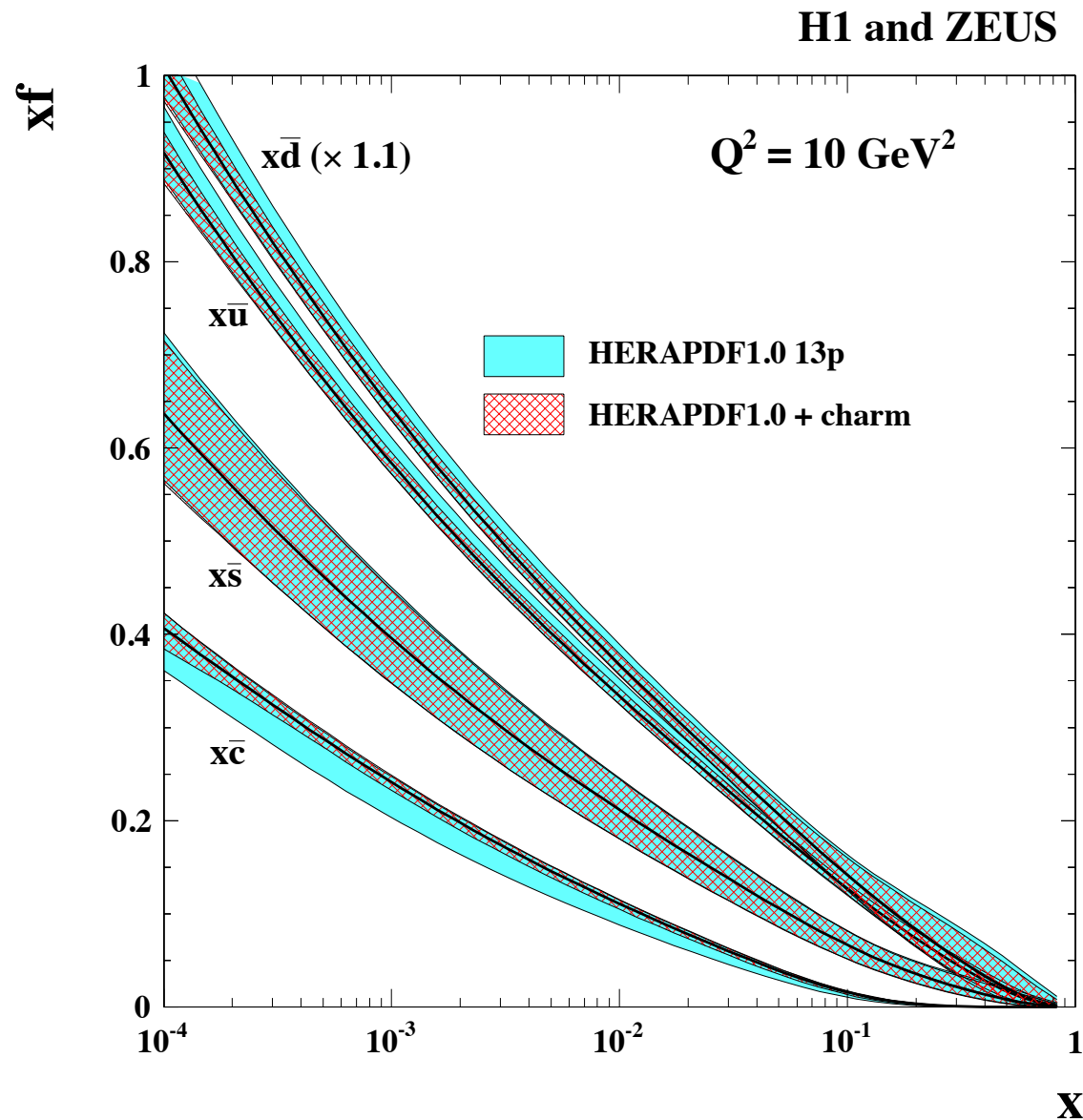
CT10 Charm Predictions

HERAPDF1.0+charm: uncertainties
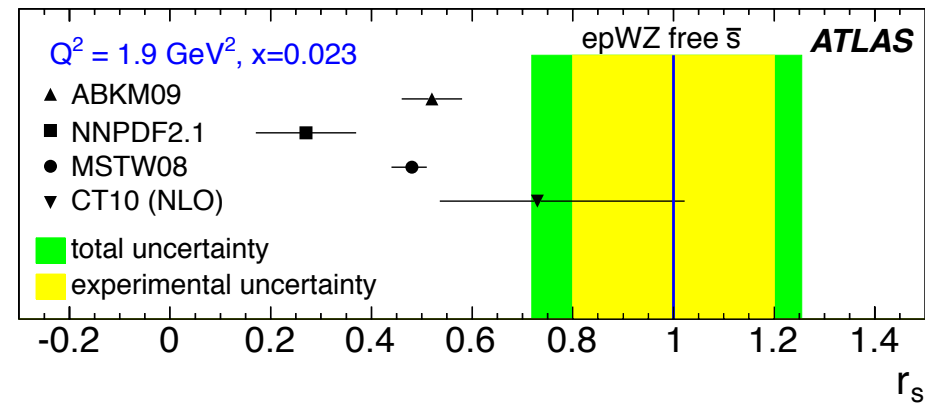
HERAFitter: Determination of the strange density in the proton

The differential W and Z cross sections measured by ATLAS (35 pb^{-1}) were jointly analysed with HERA inclusive $e^{\pm}p$ cross sections

Ratio of W/Z cross sections together with y_Z shape provide a constraint on the s-quark density

First LHC publication using HERAFitter

Phys.Rev.Lett. 109 (2012) 012001

Measurement of $F_2^{\gamma Z}$, $F_3^{\gamma Z}$

$F_2^{\gamma Z}$:

$$\frac{\sigma^{\pm}(P_L^{\pm}) - \sigma^{\pm}(P_R^{\pm})}{P_L^{\pm} - P_R^{\pm}} = \frac{\kappa Q^2}{Q^2 + M_Z^2} \left[\mp a_e F_2^{\gamma Z} + \frac{Y_-}{Y_+} v_e x F_3^{\gamma Z} - \frac{Y_-}{Y_+} \frac{\kappa Q^2}{Q^2 + M_Z^2} (v_e^2 + a_e^2) x F_3^Z \right]$$

$F_3^{\gamma Z}$:

$$x\tilde{F}_3 = \frac{Y_+}{2Y_-} (\tilde{\sigma}^{e^- p} - \tilde{\sigma}^{e^+ p}). \qquad x\tilde{F}_3 \simeq -a_e \chi_Z x F_3^{\gamma Z}.$$

Averaging procedure

Described in detail in arXiv:0904.0929

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

For multiplicative error sources small biases to lower cross sections values may occur. This can be avoided modifying the χ^2 definition as follows:

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

with $\quad \gamma^i_j = \Gamma^i_j/\mu^i \qquad \delta_{i,\text{stat}} = \Delta_{i,\text{stat}}/\mu^i \qquad \delta_{i,\text{uncor}} = \Delta_{i,\text{uncor}}/\mu^i$