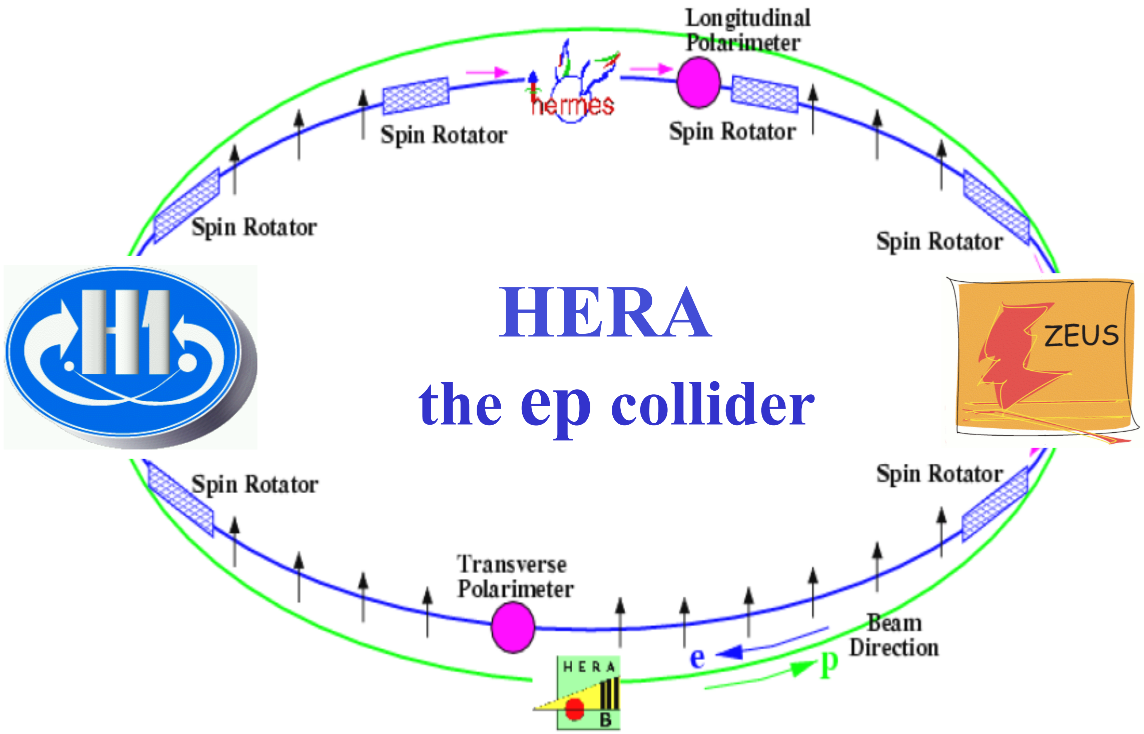
Proton Structure and PDFs at HERA

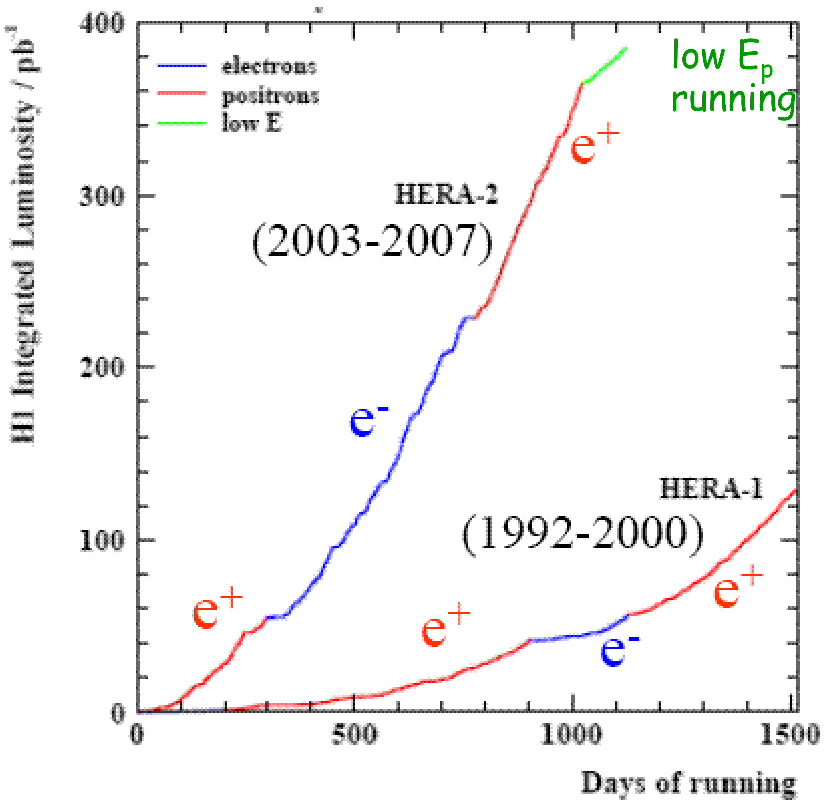
Vladimir Chekelian (MPI for Physics, Munich)

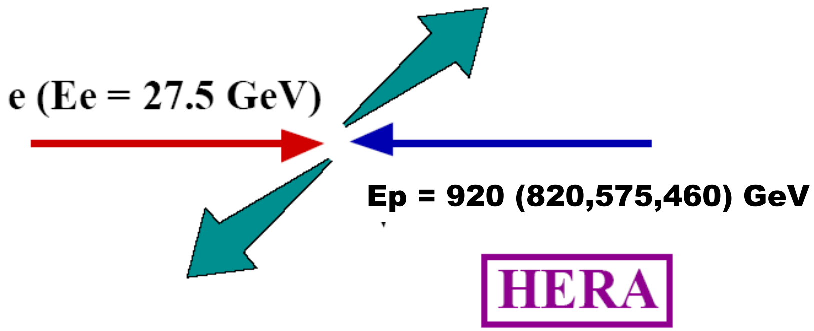
on behalf of the H1 and ZEUS Collaborations



- HERA / DIS / NC / CC
- Inclusive ep Cross Sections
- Proton Structure Functions
- HERAPDF
- Charm Production
- HERAFitter
- Summary

The ep collider HERA (1992–2007)





located at DESY, Hamburg
peak luminosity 5 10^{31} cm^{-2} sec^{-1}
$Q^2_{max} = 10^5$ GeV^2
$\lambda_{min} \sim 1/1000\ r_{proton}$
longitudinal polarisation of e-beam

HERA I	1992-2000	~120 pb-1
HERA II	2003-2007	~380 pb-1

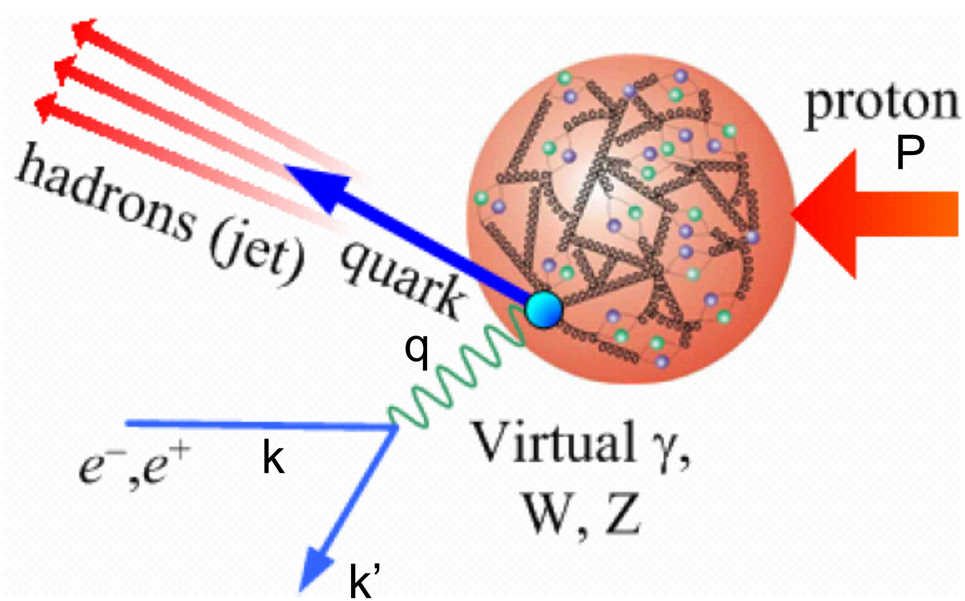
H1+ZEUS in total 2 x 0.5 fb^{-1}

about equally shared between

- **e^+ and e^-,**
- **positive and negative P_e**

low proton energy running for F_L

Deep Inelastic Scattering (DIS)



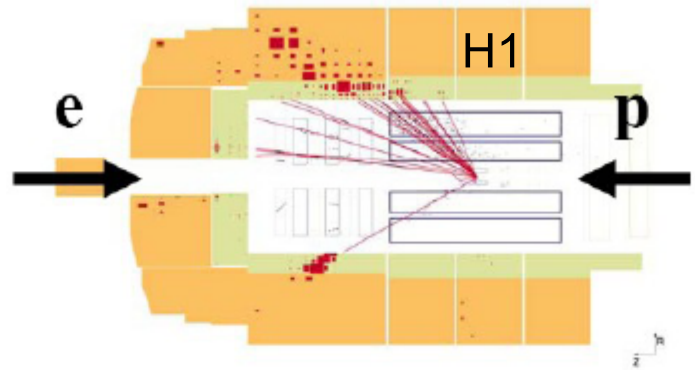
$Q^2 = -q^2 = -(k-k')^2$ virtuality of γ^*, Z^0, W

$x = Q^2/2(Pq)$ Bjorken x

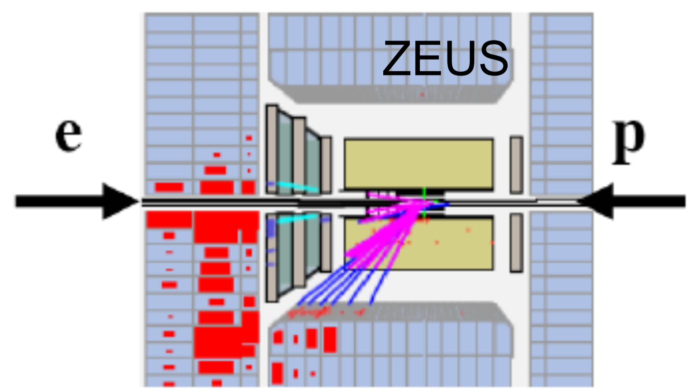
$y = (Pq)/(Pk)$ inelasticity

$Q^2 = sxy$ $s=(k+P)^2$

Neutral Current (NC): $e^{\pm}p \rightarrow e^{\pm}X$



Charged Current (CC): $e^{\pm}p \rightarrow \nu X$



Factorisation: $\sigma_{DIS} : \hat{\sigma} \otimes pdf(x)$

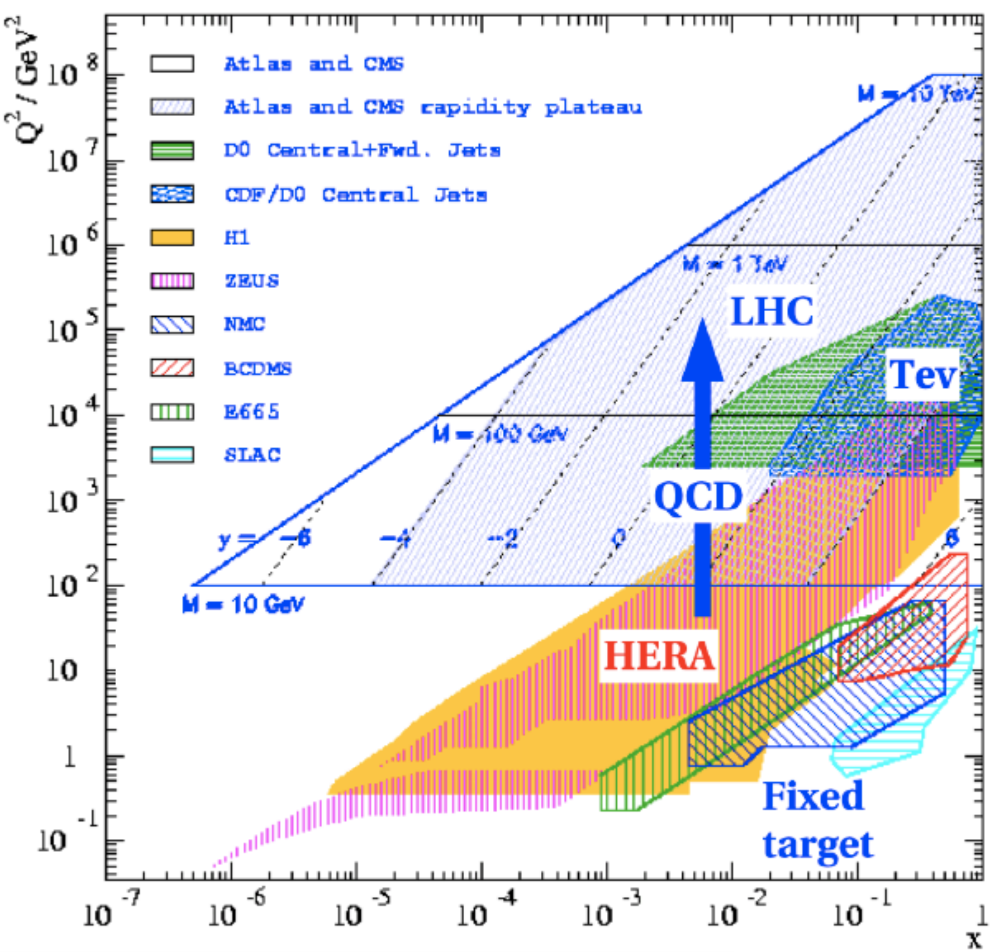
$\hat{\sigma}$ – perturbative QCD cross section

pdf – universal parton distribution functions

PHOTON 2013
Paris 20.05.2013

Q^2-x plane at HERA

HERA: span 5 orders of magnitude in x and Q^2



Inclusive data sets from H1 and ZEUS cover different parts of the phase space are obtained in different periods using different detector components, different beam energies and polarisation.

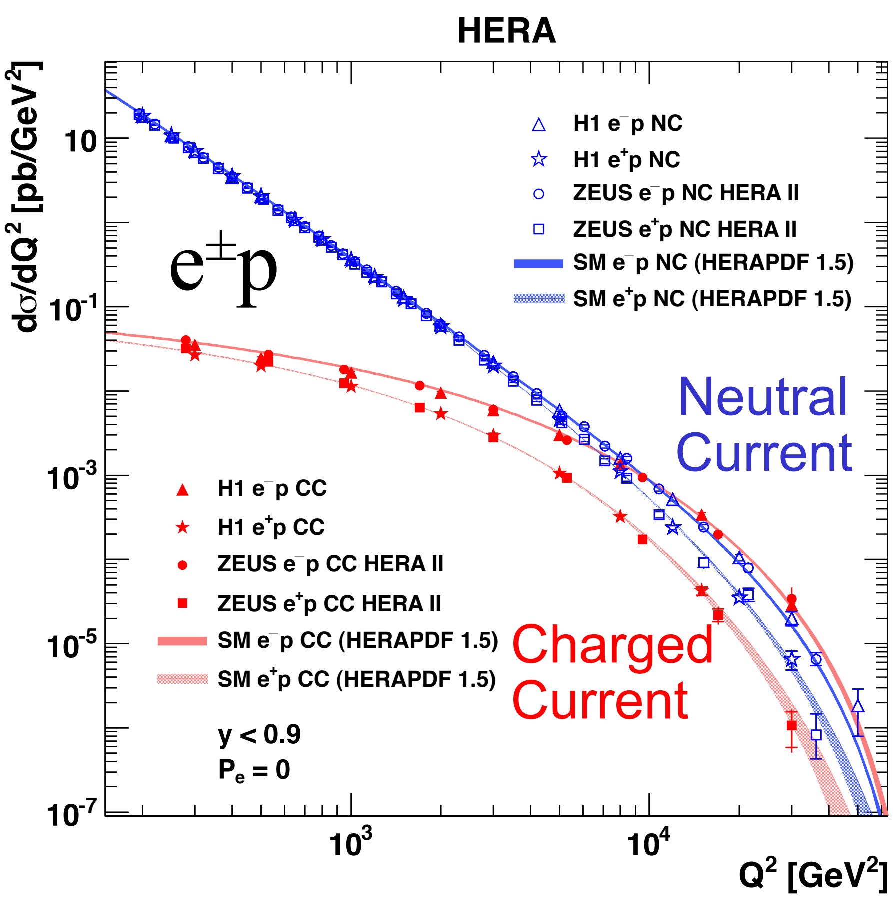
HERA I (1994-2000) inclusive NC & CC analyses are completed, published both by H1 and ZEUS and combined.

HERA II (2003-2007) NC & CC analyses with longitudinally polarised lepton beams are completed in 2012 and published both by H1 and ZEUS

Full HERA x range is important for the LHC

→ HERA inclusive data are an indispensable input to modern QCD PDF fits

Inclusive NC & CC at HERA



$\sigma_{NC} \approx \sigma_{CC}$ at $Q^2 \gtrsim M_Z^2, M_W^2$

→ remaining differences are due to u/d flavor asymmetry and helicity factors

$$\tilde{\sigma}^{\pm}_{NC} \equiv \frac{d^2\sigma^{e^\pm p}_{NC}}{dx dQ^2}\frac{xQ^4}{2\pi\alpha^2}\frac{1}{Y_+} \equiv \tilde{F}_2 - \frac{y^2}{Y_+}\tilde{F}_L \mp \frac{Y_-}{Y_+}x\tilde{F}_3$$

$$F_2(x,Q^2) = x\sum A_i(q_i+\bar{q}_i) \qquad xF_3(x,Q^2) = x\sum B_i(q_i-\bar{q}_i)$$

$$F_L = F_2 - 2xF_1 = 0 \quad \text{(QPM)} \qquad Y_\pm = 1 \pm (1-y)^2$$

→ all three SF are measured at HERA

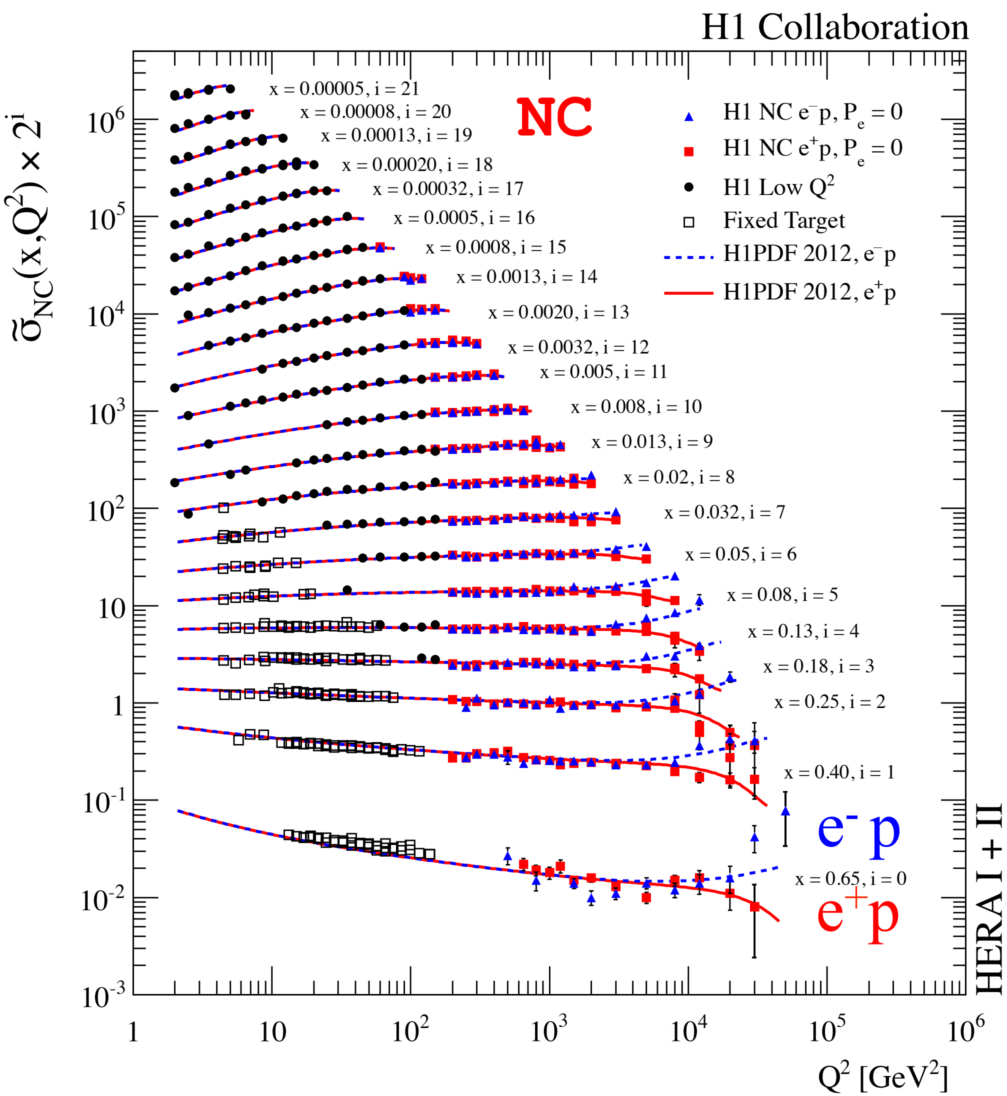
$$\tilde{\sigma}_{CC} = \frac{2\pi x}{G_F^2}\left[\frac{M_W^2+Q^2}{M_W^2}\right]^2 \frac{d^2\sigma_{CC}}{dx dQ^2}$$

$$\tilde{\sigma}^{+}_{CC} \sim (x\bar{u} + x\bar{c}) + (1-y)^2(xd + xs)$$

$$\tilde{\sigma}^{-}_{CC} \sim (xu + xc) + (1-y)^2(x\bar{d} + x\bar{s})$$

→ CC data allow flavor separation in QCD fits

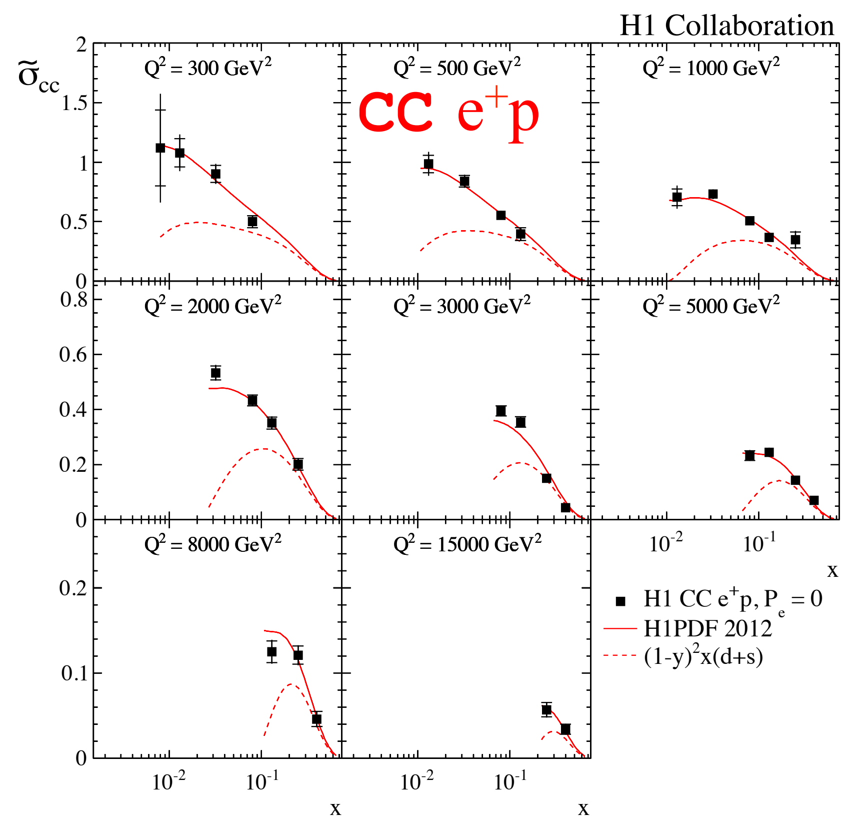
NC and CC Cross Sections $\sigma_{NC,CC}(x,Q^2)$



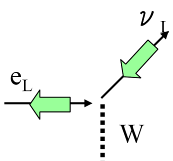
H1 and ZEUS completed the HERA II NC&CC measurements:

H1: JHEP 09 (2012) 061

ZEUS: PRD 87 (2013) 052014 EPJ C61 (2009) 223 EPJ C62 (2009) 625 EPJ C70 (2010) 945

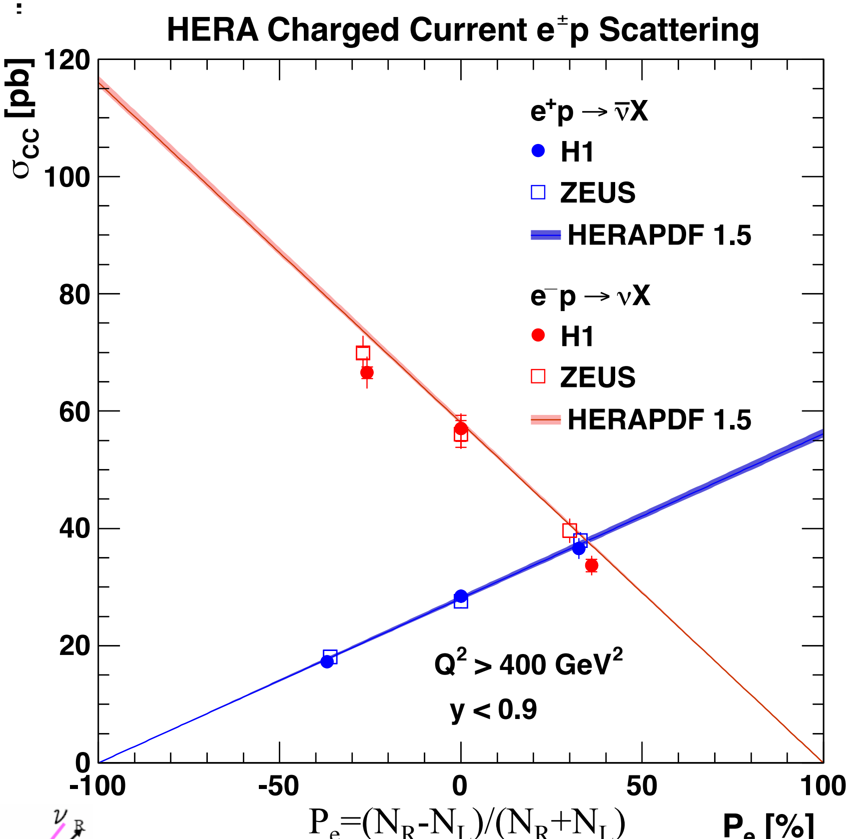


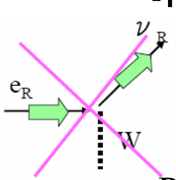
Polarisation effects in CC and NC



Polarisation dependence of the total CC cross section

$$\sigma_{CC}^{e^\pm p} = (1 \pm P_e)\sigma_{CC}^{e^\pm p}(P_e = 0)$$

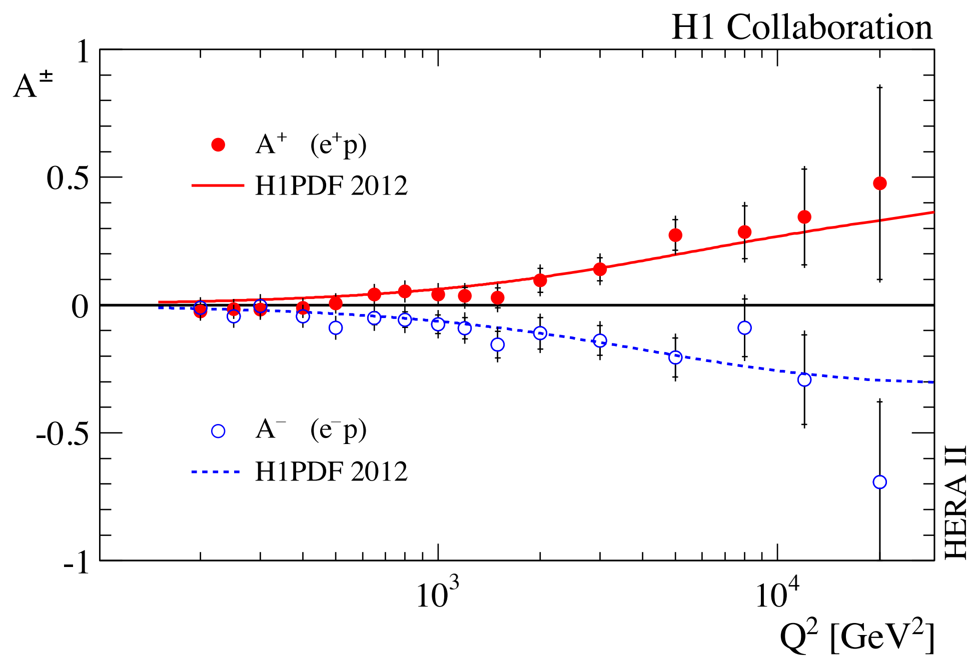




→ absence of right-handed weak current

Polarisation asymmetry in NC:

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



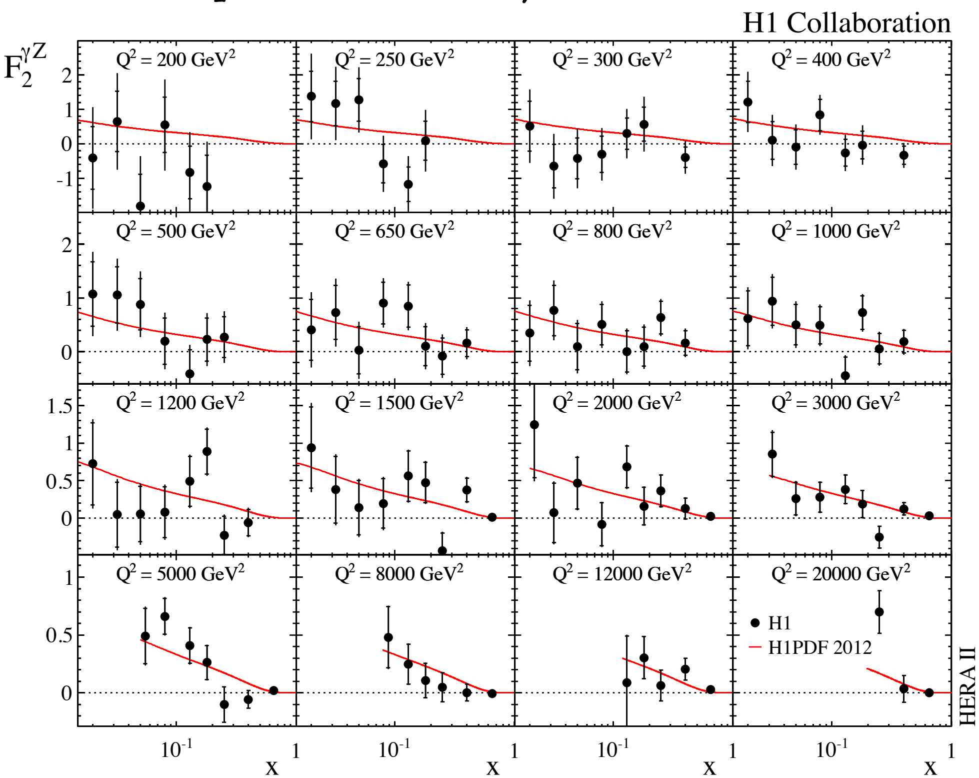
→ a direct measure of parity violation in NC

The First Measurement of Parity Violating SF $F_2^{\gamma Z}(x,Q^2)$

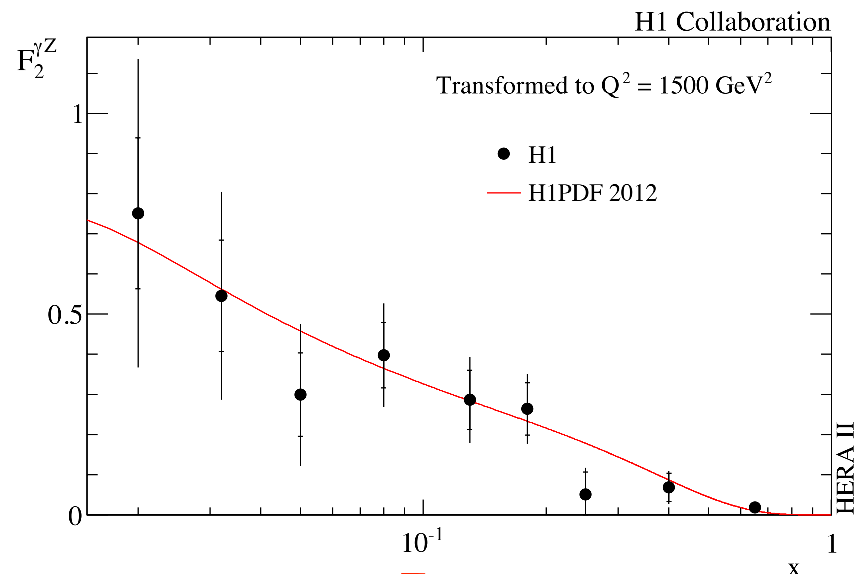
$$\frac{\sigma^{\pm}(P_L^{\pm}) - \sigma^{\pm}(P_R^{\pm})}{P_L^{\pm} - P_R^{\pm}} = \frac{\kappa Q^2}{Q^2 + M_Z^2}\left[\mp a_e F_2^{\gamma Z} + \frac{Y_-}{Y_+} v_e x F_3^{\gamma Z} - \frac{Y_-}{Y_+}\frac{\kappa Q^2}{Q^2 + M_Z^2}(v_e^2 + a_e^2) x F_3^Z\right]$$

taking the difference for e^+p and e^-p, the terms with $xF_3^{\gamma Z}$ and xF_3^Z cancel and $F_2^{\gamma Z}$ can be directly extracted from measured polarised cross sections

$$\kappa^{-1} = 4\frac{M_W^2}{M_Z^2}\left(1 - \frac{M_W^2}{M_Z^2}\right)$$



transform the $F_2^{\gamma Z}(x,Q^2)$ measurements to Q^2 = 1500 GeV^2 and average them to get $F_2^{\gamma Z}(x)$ at Q^2 = 1500 GeV^2



→ $F_2^{\gamma Z} = x\sum[2e_q v_q(q+\bar{q})]$

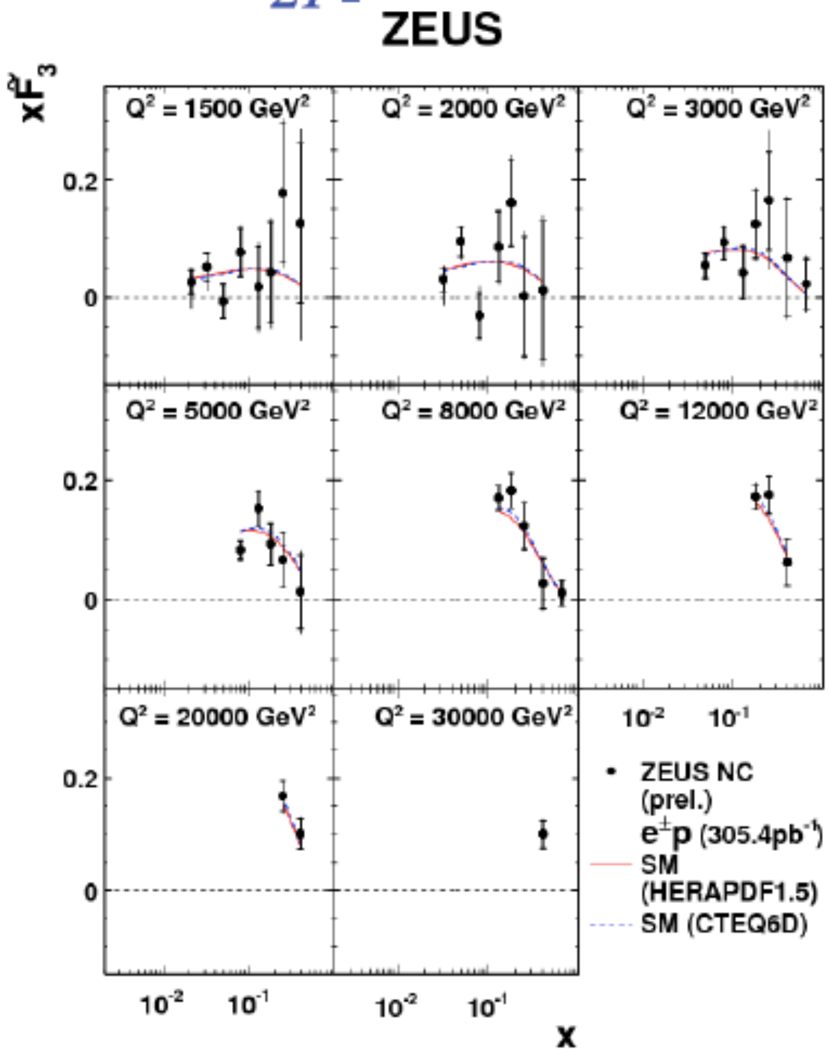
Structure Function $xF_3(x,Q^2)$

$$x\tilde{F}_3 = \frac{Y_+}{2Y_-}\left(\tilde{\sigma}^-_{NC} - \tilde{\sigma}^+_{NC}\right)$$

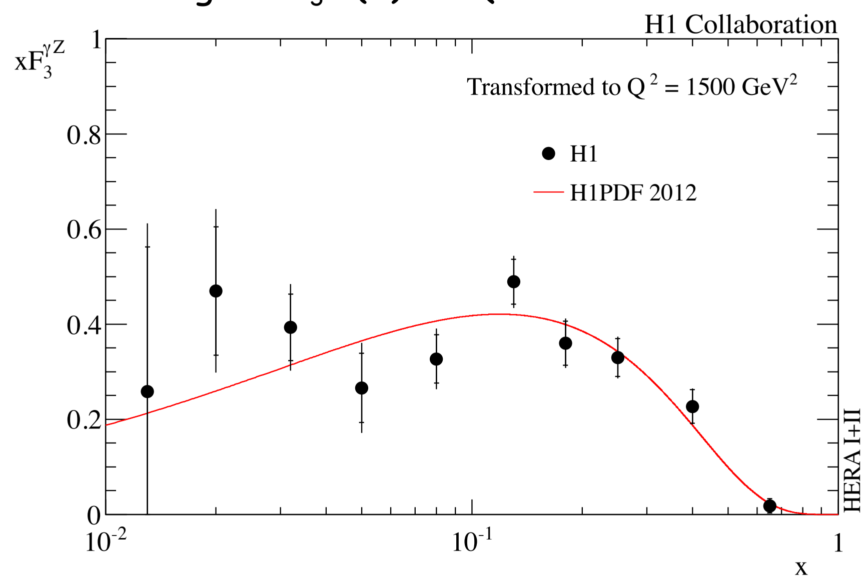
- charge asymmetry of unpolarised $e^{\pm}p$ NC cross sections

→ *mostly due to γZ interference*

$$xF_3^{\gamma Z} = -x\tilde{F}_3 \cdot (Q^2 + M_Z^2)/(a_e \kappa Q^2)$$



transform the $xF_3^{\gamma Z}(x,Q^2)$ measurements to Q^2 = 1500 GeV^2 and average them to get $xF_3^{\gamma Z}(x)$ at Q^2 = 1500 GeV^2



→ sensitive to valence quark: $F_3^{\gamma Z} \approx (2u_v+d_v)/3$

$$\int_{0.016}^{0.725} dx\, F_3^{\gamma Z}(x, Q^2 = 1\,500\,\mathrm{GeV}^2) = 1.22 \pm 0.09(\mathrm{stat}) \pm 0.07(\mathrm{syst})$$

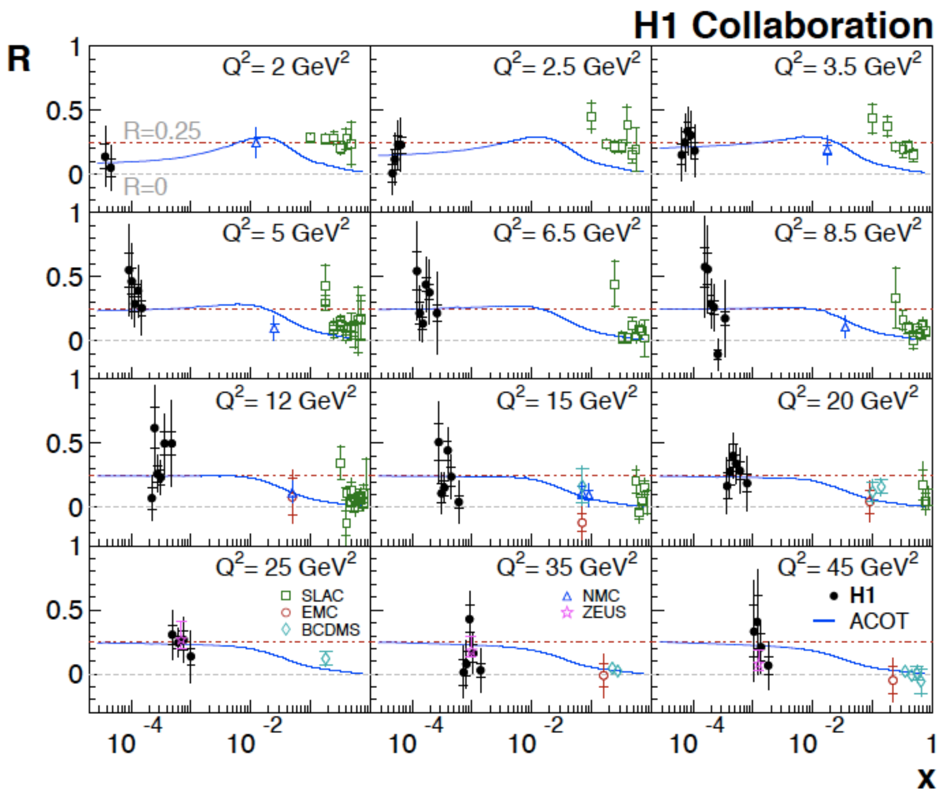
(H1PDF2012: 1.16+0.02-0.03)

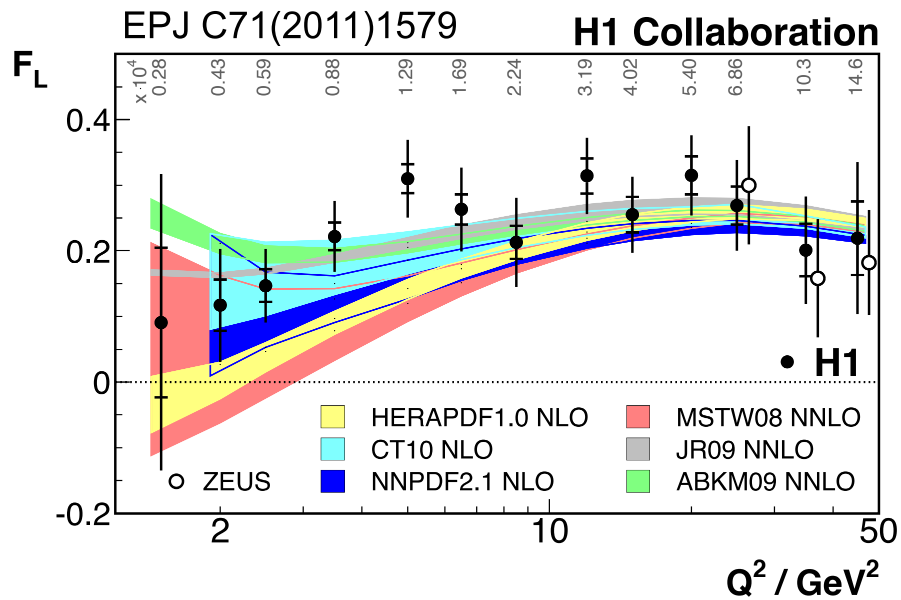
The longitudinal structure function $F_L(x,Q^2)$

- F_L is a pure QCD effect sensitive to gluon density $F_L(x,Q^2) = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3}\left[\frac{16}{3}F_2 + 8\sum_q e_q^2 (1-\frac{x}{z}) \cdot xg\right]$

- F_L is measured at HERA using cross sections at the same x, Q^2 and different y (different proton beam energies Ep = 460, 575, 920 GeV)

$$\sigma_{NC}(x,Q^2,y) = F_2(x,Q^2) - f(y)\, F_L(x,Q^2)\ , \quad f(y)=y^2/(1+(1-y)^2)$$





→ HERA F_L data are consistent with constant value of $R=F_L/(F_2-F_L)=0.26\pm0.05$

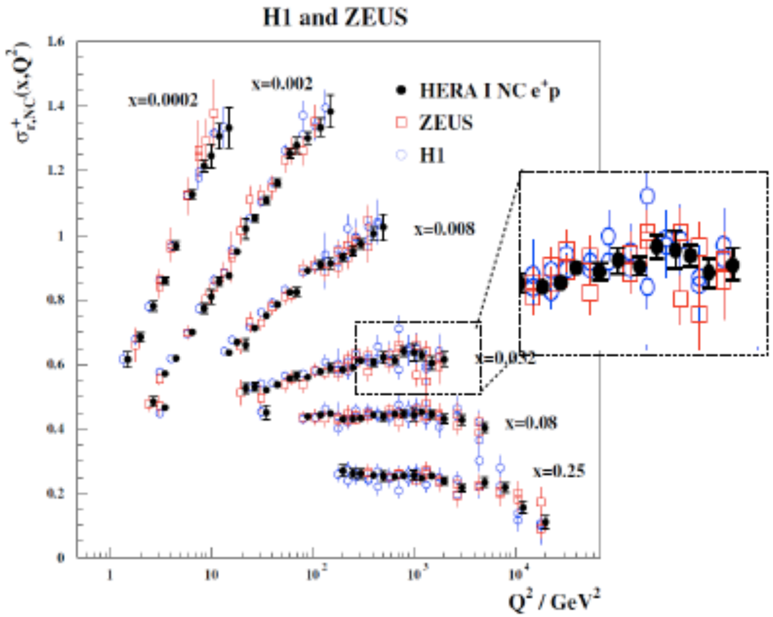
HERAPDF: QCD Fits using HERA data only

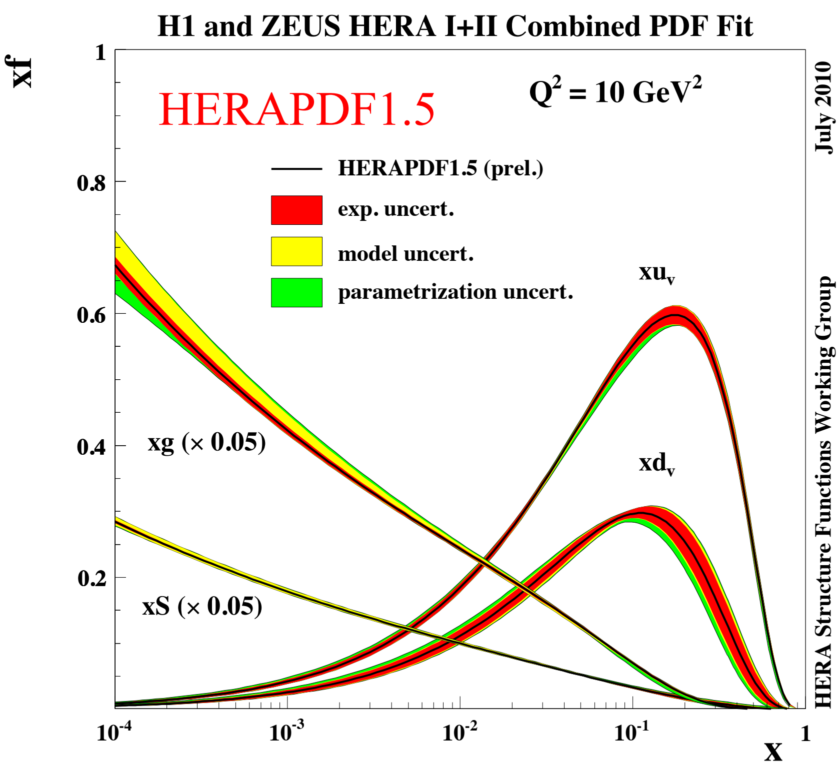
Input: **combined H1 & ZEUS incl. NC and CC data** which include expert knowledge in the treatment of the correlations between many individual data sets.

→ precise, complete and easy in use

→ significant reduction of systematic uncertainties

1. HERA I data: JHEP 1001:109,2010 HERAPDF 1.0
2. HERA I and preliminary HERA II data HERAPDF 1.5

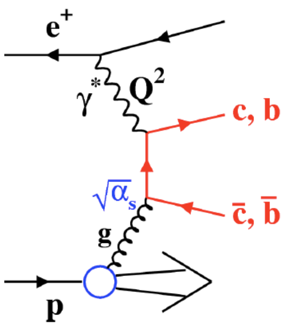




HERAPDF

- no nuclear corrections
- no heavy target correction
- $\Delta\chi^2 = 1$ criterion for exp. errors
- parametrise $xg(x), xu_v, xd_v, xUbar, Dbar$ at starting scale Q_0^2
- apply quark number and momentum sum rules
- NLO/NNLO DGLAP evolution
- different schemes for heavy flavor treatment
- uncertainty bands:
  - experimental
  - model (variations of Q^2_{min}, f_s, m_c, m_b)
  - parameterisation (variation of param. assumptions)

Combination of charm data at HERA



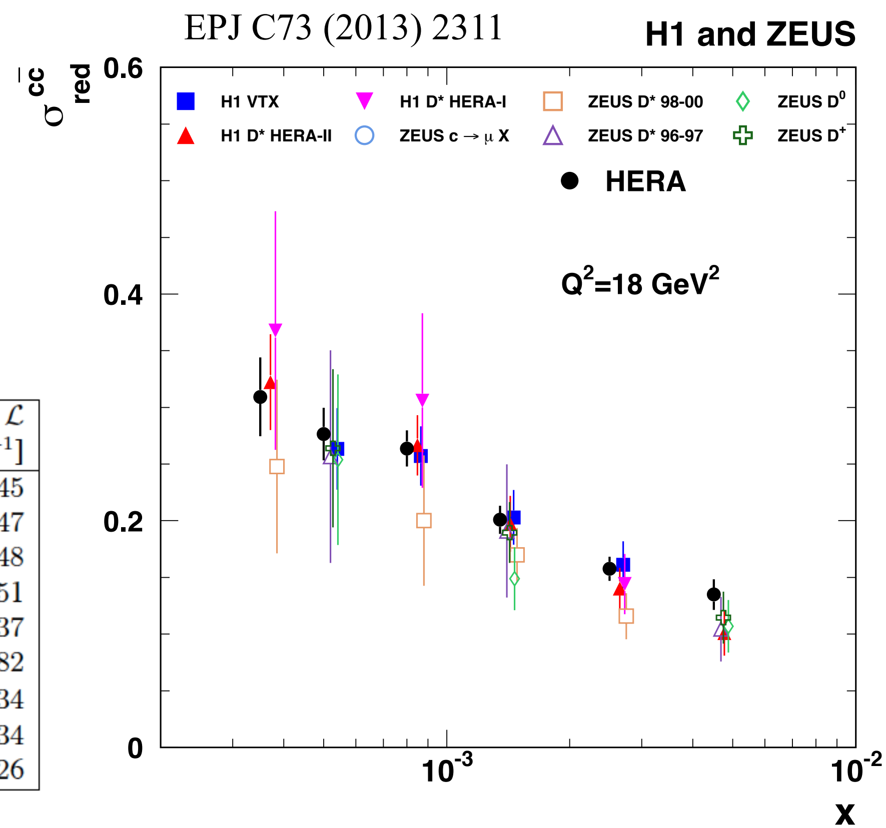
Up to 30% of the inclusive cross section is related to charm production

→ important for QCD evolution and PDF fits

Combine different H1 and ZEUS measurements
- reconstruction of D* and D decays
- inclusive analysis of tracks lifetime information
- muons from charm semi-leptonic decays

	Data set	Tagging method	Q^2 range [GeV^2]	N	$\mathcal{L}$ [pb^{-1}]
1	H1 VTX [14]	Inclusive track lifetime	5 – 2000	29	245
2	H1 D^* HERA-I [10]	D^{*+}	2 – 100	17	47
3	H1 D^* HERA-II [18]	D^{*+}	5 – 100	25	348
4	H1 D^* HERA-II [15]	D^{*+}	100 – 1000	6	351
5	ZEUS D^* (96-97) [4]	D^{*+}	1 – 200	21	37
6	ZEUS D^* (98-00) [6]	D^{*+}	1.5 – 1000	31	82
7	ZEUS D^0 [12]	$D^{0,\mathrm{no}D^{*+}}$	5 – 1000	9	134
8	ZEUS D^+ [12]	D^+	5 – 1000	9	134
9	ZEUS μ [13]	μ	20 – 10000	8	126

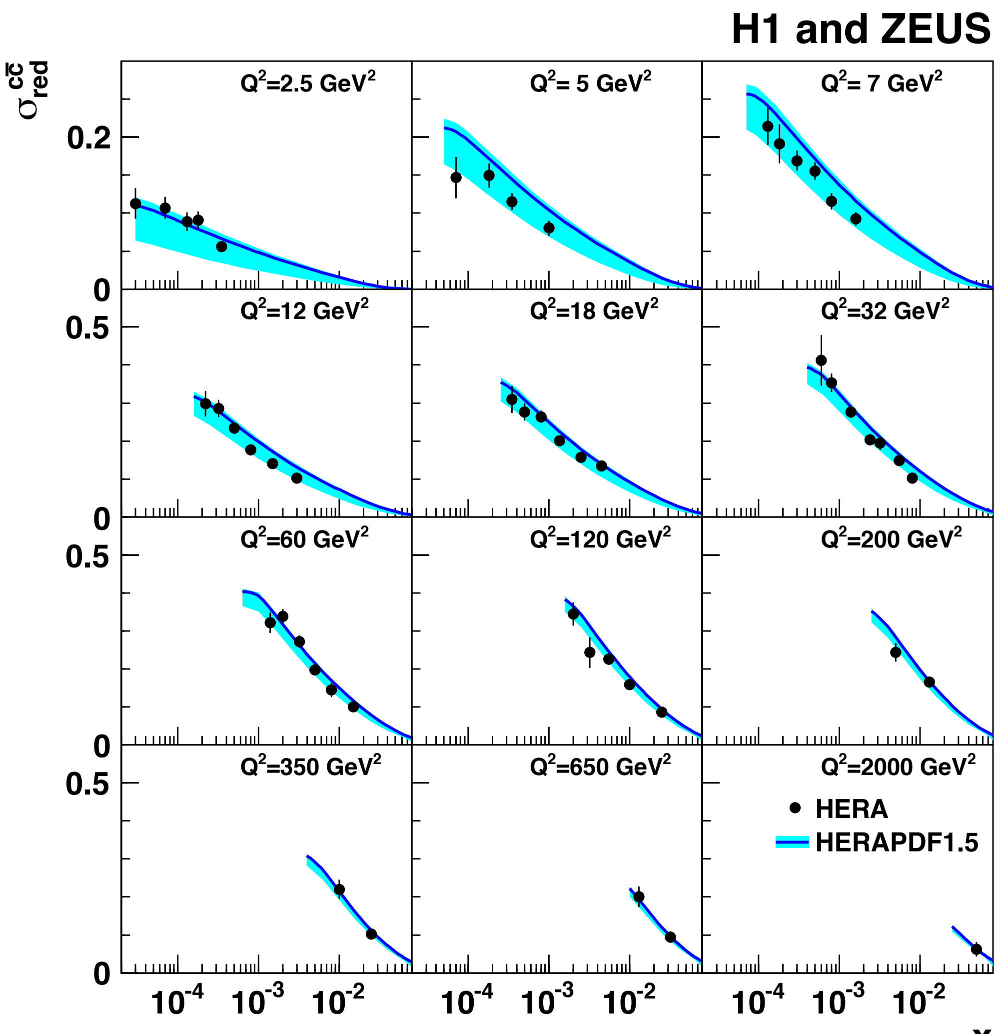
Example of combination of charm data



Extension of visible cross section (D*, D, μ) to the full phase space at given x and Q2 using HVQDIS and pdfs according to FFNS version of HERAPDF1.0 at NLO

→ Precision of the combined data is two times better than each of the most precise individual data sets in the combination

Charm contributions to proton str. functions $F^{cc}_{2(L)}$



$$\sigma^{c\bar{c}}_{\rm red} = \frac{d^2\sigma^{c\bar{c}}}{dx\,dQ^2} \cdot \frac{xQ^4}{2\pi\alpha^2(Q^2)\,(1+(1-y)^2)} = F_2^{c\bar{c}} - \frac{y^2}{1+(1-y)^2} F_L^{c\bar{c}}$$

FFNS: Fixed Flavour Number Scheme
three light quarks (u,d,s) and
massive c,b (boson-gluon fusion)

Global fit ABM ($\overline{MS}$ running mass $m_c(m_c)$)

VFNS: Variable Flavour Number Scheme
from three to five active quarks (u,d,s.c.b)
c,b massive at low Q2, massless at high Q2
→ different approximations (matching) in between

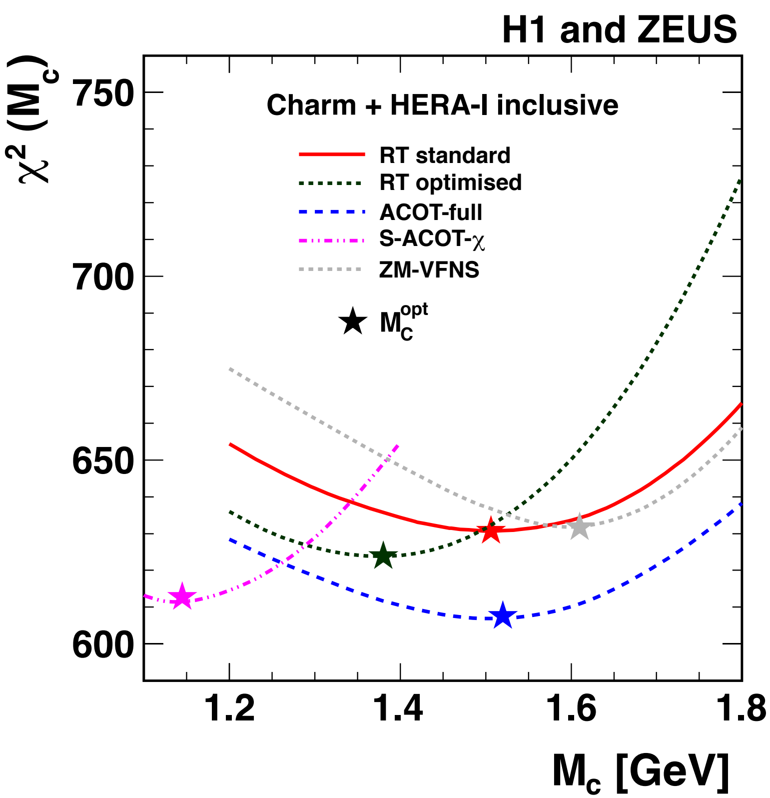
Global fits MSTW, CTEQ, NNPDF
pole mass (PDG : m_c=1.67)
m_c=1.4 GeV recommended by RT

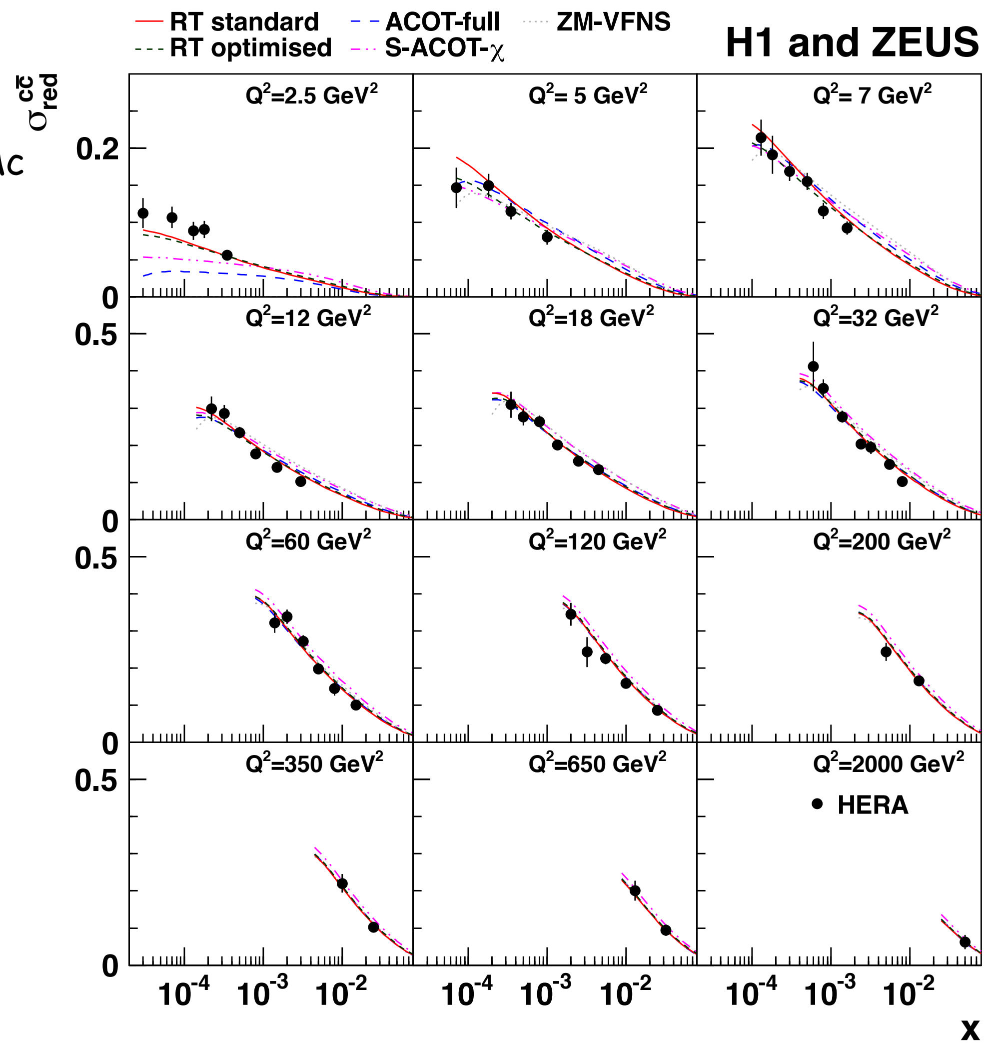
→ described well by HERAPDF1.5 fit to inclusive data (VFNS)
→ large error band due to 1.35 < Mc < 1.65 GeV

consider Mc as an additional effective parameter →

Optimal charm mass parameter M_c

χ2 scans of the QCD fits with different implementations of the VFNS to HERA I inclusive data and to combined charm data as function of the charm mass parameter Mc

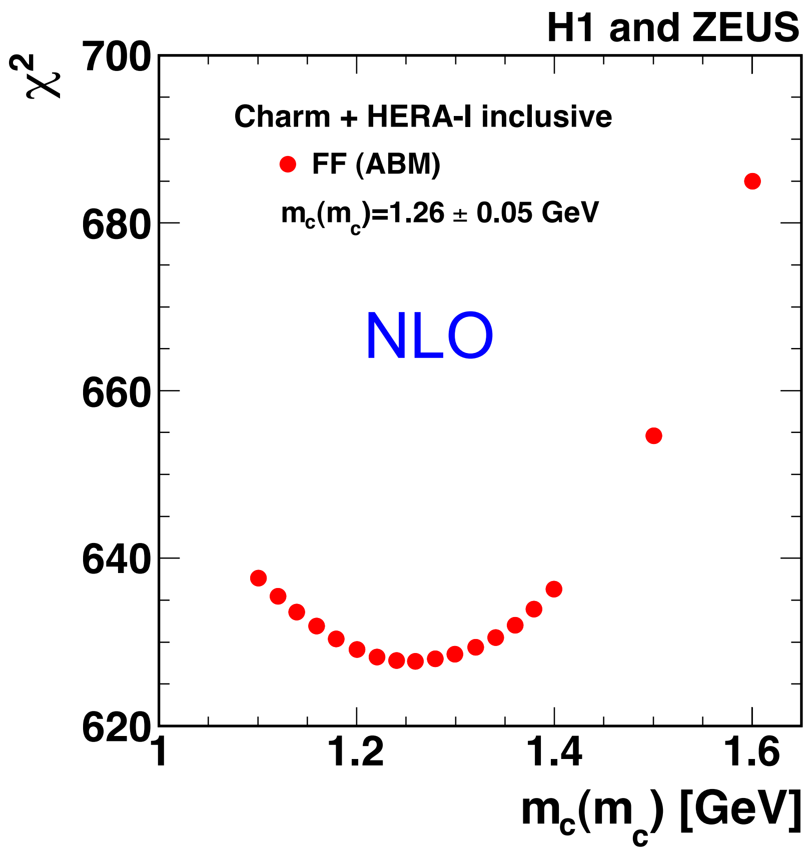




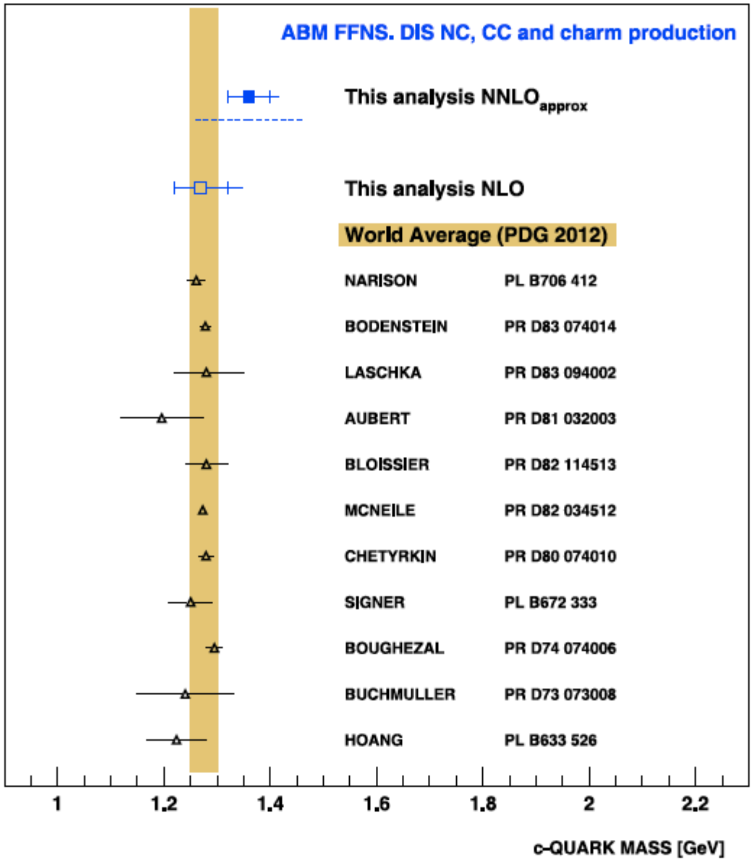
→ good description of the charm data at Q2 ≥ 5 GeV2 using optimal mass corresponding to min χ2

Measurement of charm mass in DIS ($\overline{MS}$ scheme)

In FFNS, $\overline{MS}$ running mass $m_c(m_c)$ is a well defined physics concept with clear relation to the pole mass

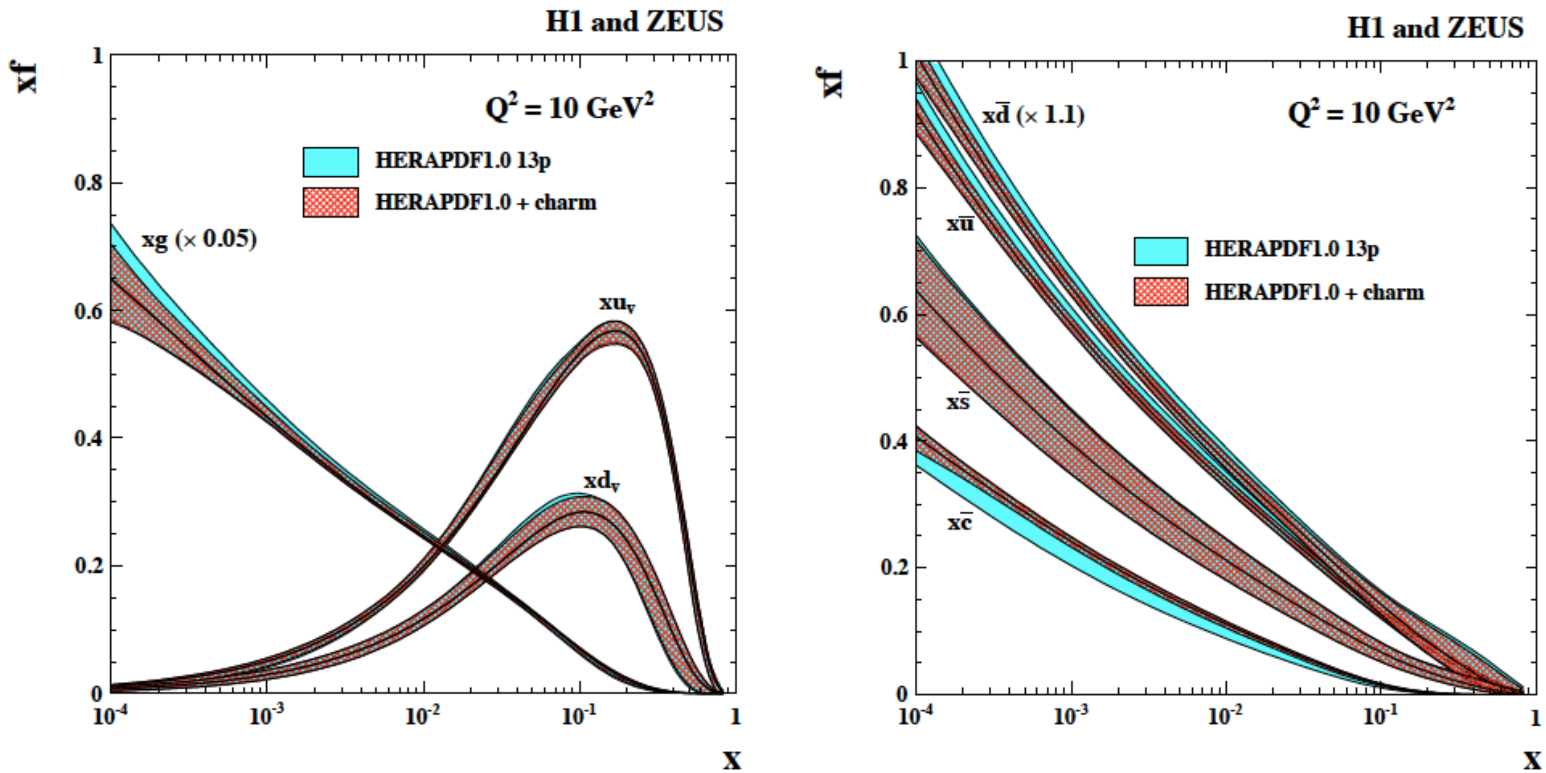


S.Alekhin et al. PLB 718 (2012) 550



→ charm mass from DIS in the FFN scheme is in a good agreement with e+e- and lattice
→ comparable precision with world average.

Impact of the charm data on PDFs

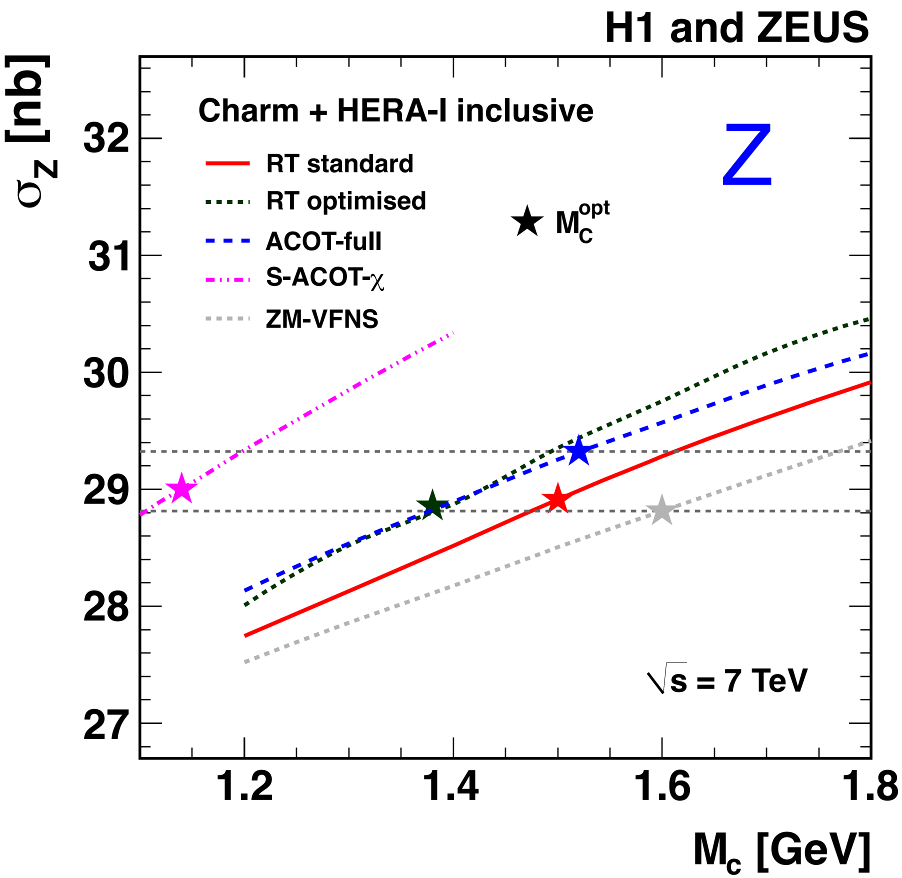


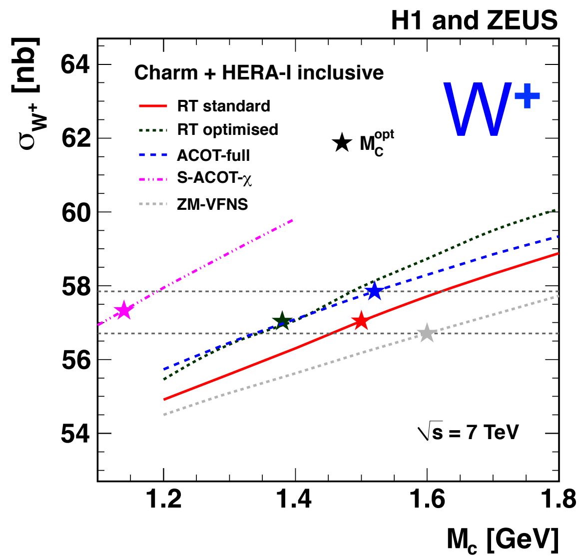
→ charm distribution function uncertainty is drastically reduced
→ impact on gluon (through γg → cc) and light sea

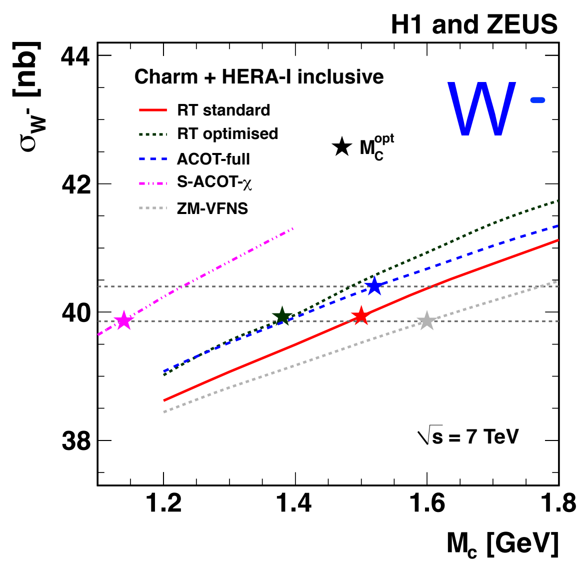
Z, W cross section predictions for LHC

For different implementations of VFNS:
spread of 6% at fixed value of Mc = 1.4 GeV

→ optimal Mc reduces uncertainty to below 2%



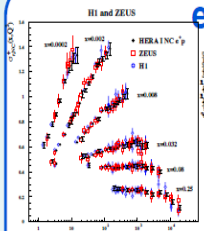


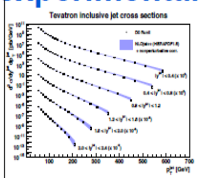


HERAFitter Project

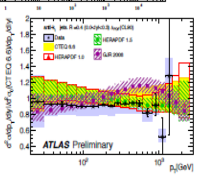
HERAFitter project is an open source QCD fit framework ready to extract PDFs and assess the impact of new data

experimental input





experiments:
HERA, Tevatron, LHC, fixed target



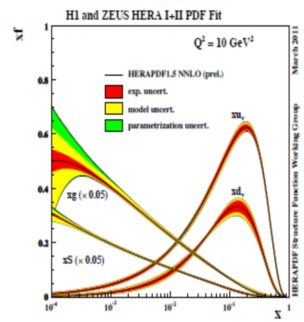
processes:
NC, CC DIS, jets, diffraction, heavy quarks (c,b,t)
Drell-Yan, W production

theoretical calculations/tools

Heavy quark schemes:	MSTW, CTEQ, ABM
Jets, W, Z production:	fastNLO, Applgrid
Top production	NNLO (Hathor)
QCD Evolution	DGLAP (QCDNUM)
	k_T factorisation
Alternative tools	NNPDF reweighting
Other models	Dipole model

+ Different error treatment models
+ Tools for data combination (HERAaverager)

HERAFitter



PDF or DPDF,...

$\alpha_S(M_Z), m_c, m_b, m_t, f_s,..$

Theory predictions

Benchmarking

Comparison of schemes

www.herafitter.org

H1 and ZEUS
(charm studies and HERA PDF)
EPJ C73 (2013) 2311
JHEP 1209 (2012) 061

ATLAS (s-quark density determination, jets)
PRL 109 (2012) 012001
ATLAS-CONF-2012-128

few ongoing studies in CMS

LHeC studies
J.Phys. G39 (2012) 075001

→ well integrated into the high energy community (both, experiment and theory)

Summary

- HERA I and HERA II inclusive NC and CC cross section measurements are completed and published both by H1 and ZEUS

- Combination of the H1 and ZEUS inclusive NC and CC $e^{\pm}p$ data

  all HERA I results are combined using a model independent approach leading to significant reduction of systematic uncertainties; combination is extended to include prelim. HERA II data
  → aiming for combination of the complete final HERA I+II H1&ZEUS data

- HERAPDF: QCD analyses of the HERA data only

  HERAPDF 1.0 (HERA I); HERAPDF 1.5 (HERA I + prel. HERA II, recommended), …
  → aiming for HERAPDF 2.0 using final combined inclusive data from HERA I+II

- Combined charm production cross sections in DIS at HERA

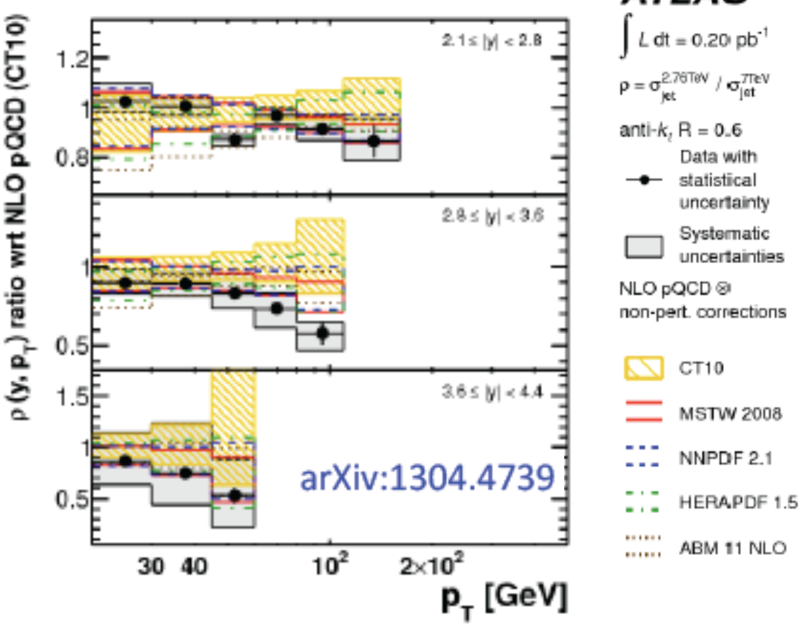
  control of the heavy quark treatment in the QCD evolution
  improve precision of PDFs, reduce uncertainties related to charm mass in predictions for LHC
  measure charm mass in the MS scheme

- HERAFitter

  an open source QCD platform ready to extract PDFs using new (LHC) data

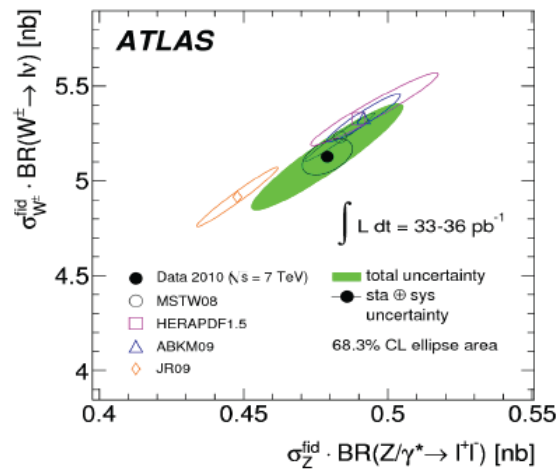
HERAPDF for LHC (few examples)

Jets



W,Z cross sections

Phys Rev D85(2012)072004



gg → H cross section

W charge asymmetry