Proton Structure and PDFs from HERA

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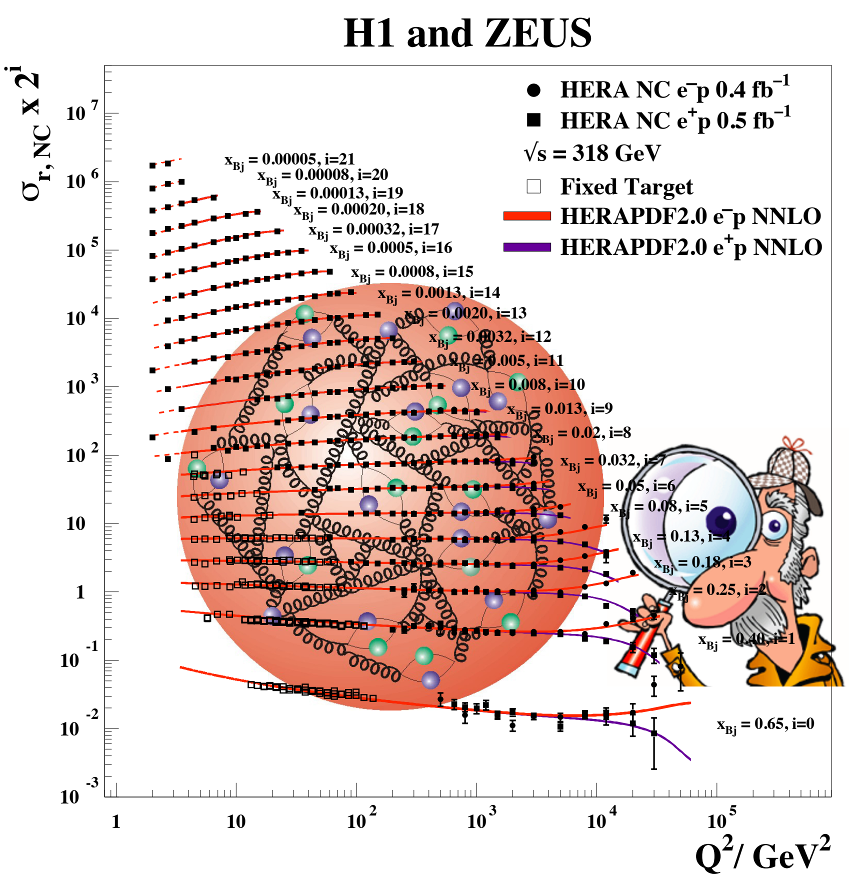
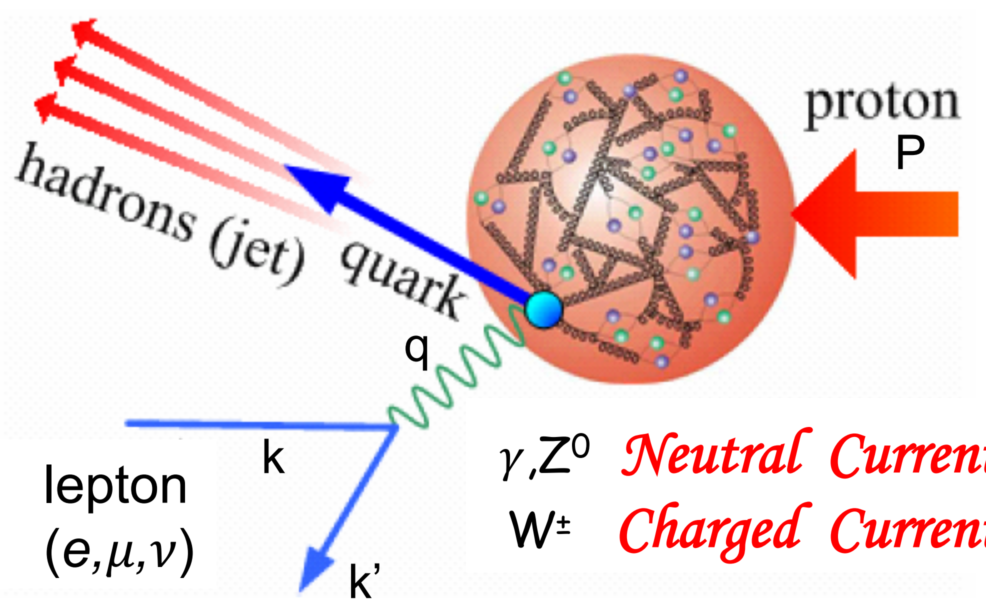
on behalf of the H1 and ZEUS Collaborations



- **DIS / Proton Structure Functions / PDFs**
- **Combination of all inclusive NC&CC data from H1&ZEUS at HERA**
- F_2, $F_2^{\gamma Z}$, $xF_3^{\gamma Z}$, F_L, σ_{CC}^{tot}, ...
- **HERAPDF 2.0 and its variants**
- **also with charm and jet HERA data;** α_s

Proton Structure Functions in Deep-Inelastic *ep/μp/νp* Scattering (DIS)



→ *inclusive DIS cross section depends on three kinematical variables:*

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

$\mathbf{x = Q^2/2(Pq)}$ Bjorken x

$\mathbf{y = (Pq)/(Pk)}$ inelasticity

$\mathbf{Q^2 = sxy}$ $s=(k+P)^2$

γ, Z^0 ***Neutral Current (NC):*** *ep → eX, μp → μX, νp → νX*

$W^\pm$ ***Charged Current (CC):*** *ep → νX, μp → νX, νp → μX*

→ *inclusive cross section can be expressed via three proton structure functions, e.g.*

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

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

QCD and Parton Distribution Functions (PDFs)

according to the QCD factorisation theorem for hard processes $\sigma = \hat{\sigma} \otimes \text{PDF}$
where universal PDFs containing long-distance structure of the proton can be measured at initial scale Q_o^2 and then be calculated at any other scale Q^2 using the QCD evolution equations, e.g. DGLAP.

In DIS inclusive cross sections are sums over partons in the proton:

F_2 – over quarks and antiquarks, xF_3 – over valence quarks

$$F_2(x,Q^2)=\sum A_q(xq+x\bar{q}) \qquad xF_3(x,Q^2)=\sum B_q(xq-x\bar{q})$$

$$F_L(x,Q^2) \propto \alpha_s \cdot xg$$ *is a pure QCD effect (in QPM $F_L=0$)*

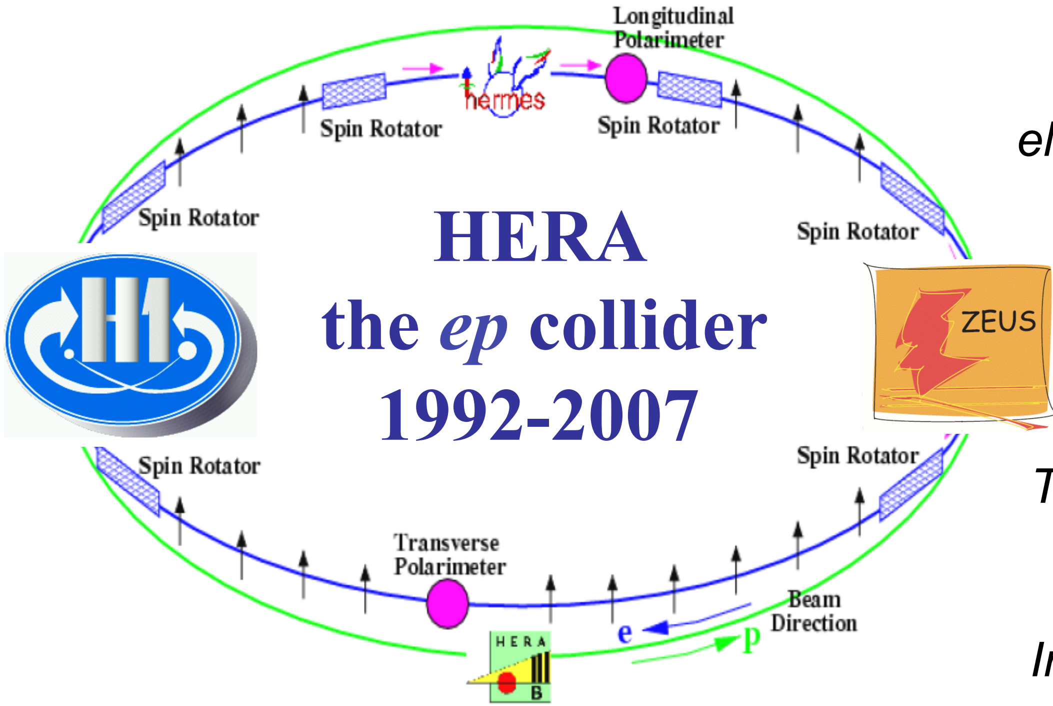
The universal parton distribution functions (of quarks of different flavor and gluon) in the proton measured in DIS can be applied to other hard processes which include proton, e.g. pp collisions at LHC

→ *PDFs are determined in QCD fits to measured cross sections*

→ *HERA inclusive DIS data are an indispensable input to any modern QCD PDF analysis*

→ *for HERAPDF the HERAFitter platform is used:* HERAFitter www.herafitter.org

The only *ep* collider HERA



15 years (1992-2007) of operation at DESY in Hamburg

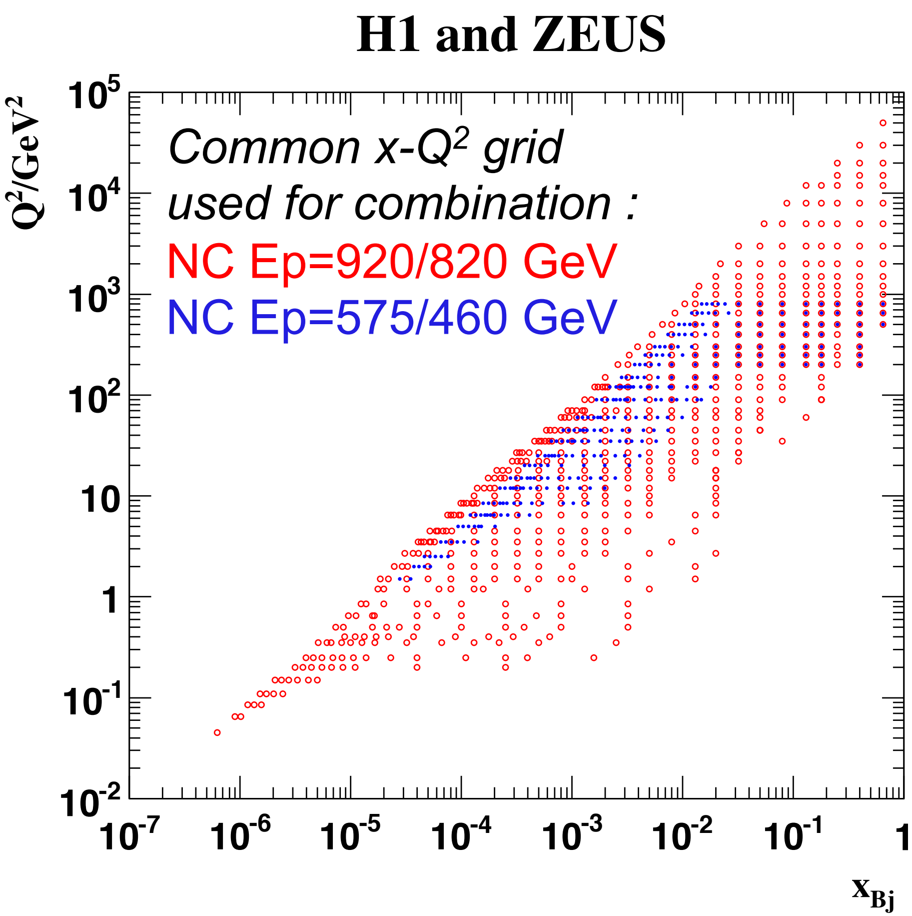
electrons & positrons of E_e=27.5 GeV collided with protons of E_p = 920, 820, 575 and 460 GeV corresponding to $\sqrt{s}$ = 318, 300, 251 and 225 GeV

Two multi-purpose collider experiments H1 & ZEUS collected in total 1 fb^{-1}.

In the second phase of HERA operation (2003-2007) the lepton beam was longitudinally polarised (~40%).

NC and CC inclusive data sets at HERA

41 NC and CC data sets from H1 and ZEUS corresponding to 1 fb^{-1}
$0.045 \le Q^2 \le 50000$ GeV^2, $6\ 10^{-7} \le x \le 0.65$



21 data sets from HERA I
NC & CC at E_p=920 and 820 GeV
and 20 data sets from HERA II (2003-2007)
12 NC & CC sets at E_p= 920 GeV
4 NC sets at E_p= 575 GeV
4 NC sets at E_p= 460 GeV

These data are collected over 15 years with changing beams and detectors conditions and different focus.
It is important to handle them properly, e.g. in view of possible correlations

→ combine them into one coherent data set as it was done for HERA I before
(JHEP 1001:109, 2010 and HERAPDF 1.0)

Averaging Procedure

The combination of all H1 and ZEUS unpolarised NC and CC data is performed using **HERAverager** (wiki-zeuthen.desy.de/HERAverager)

- the data points are moved to common x,Q^2 grid (previous slide)
- in each grid point the same cross section is expected to be measured
- all 162 systematic sources of uncertainties are treated as multiplicative in one simultaneous minimization of χ^2
- expert knowledge in the treatment of the correlations between individual data sets is taken into account

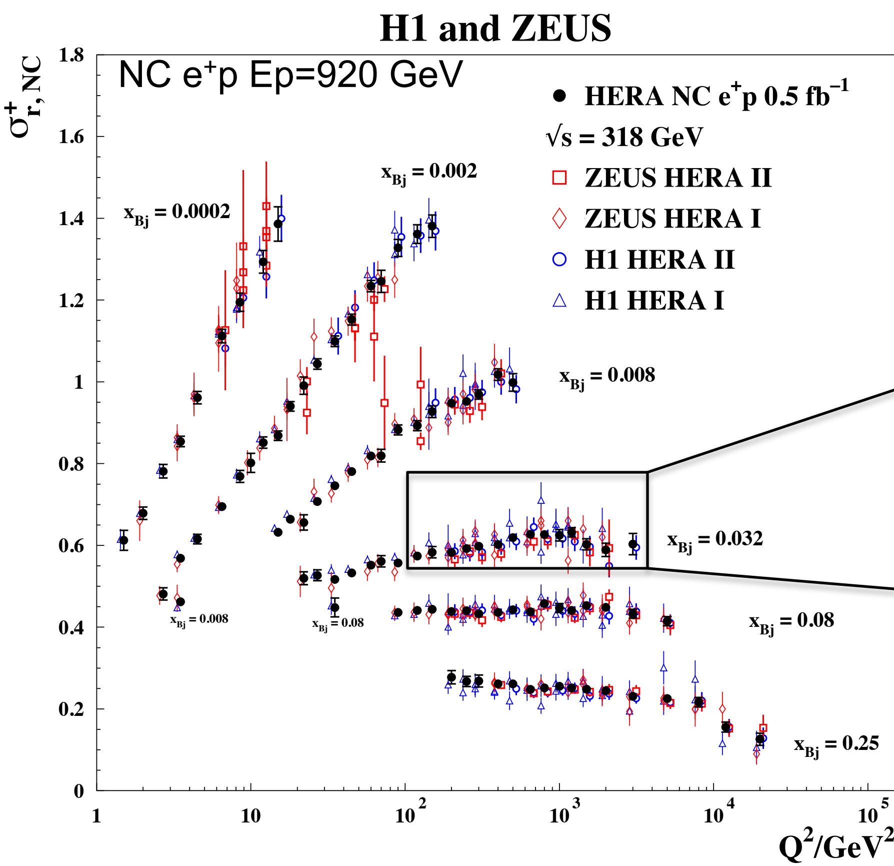
The following χ^2 definition is used:

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

7 additional procedural errors correspond to:
multiplicative vs. additive, correlation over all data sets of photoproduction bkg and hadronic energy scale uncertainties and in addition 4 procedural errors related to cross correlations between different syst. uncertainties

Averaging of all NC and CC data at HERA

2927 cross sections are combined to 1307 points with 169 correlated systematic errors and $\chi^2/d.o.f. = 1685/1620$

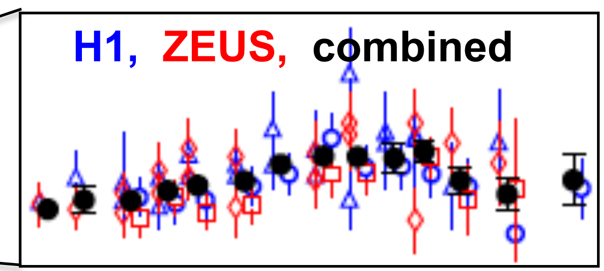


Coherent set of unpolarised $e^{\pm}p$ NC&CC at four $\sqrt{s}$ = 318, 300, 251, 225 GeV:

→ www.desy.de/h1zeus/herapdf20/

→ precise, complete and easy in use

→ with reduced stat. and syst. errors



$e^{\pm}p$ NC&CC (E_p=920 GeV)

$e^{+}p$ NC (E_p = 820, 575, 460 GeV)

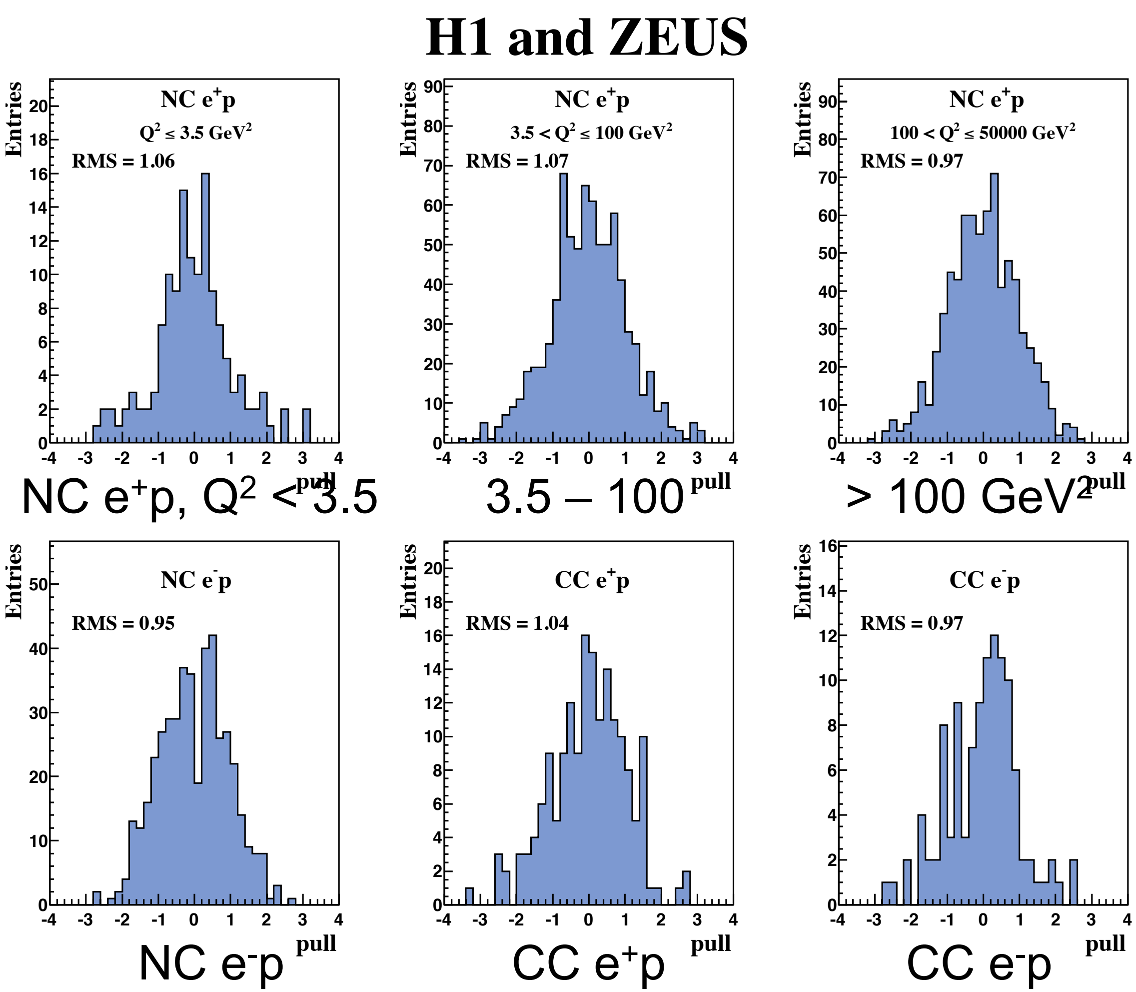
$0.045 \leq Q^2 \leq 50000$ GeV^2, $6\ 10^{-7} \leq x_{Bj} \leq 0.65$

total unc. < 1.5% for Q^2 up to 500 GeV^2

→ up to 6 measurements are combined into one averaged point

→ correlated shifts are propogated to all points (even measured by single experim.)

Consistency of the input data sets



Very good overall (close to one)

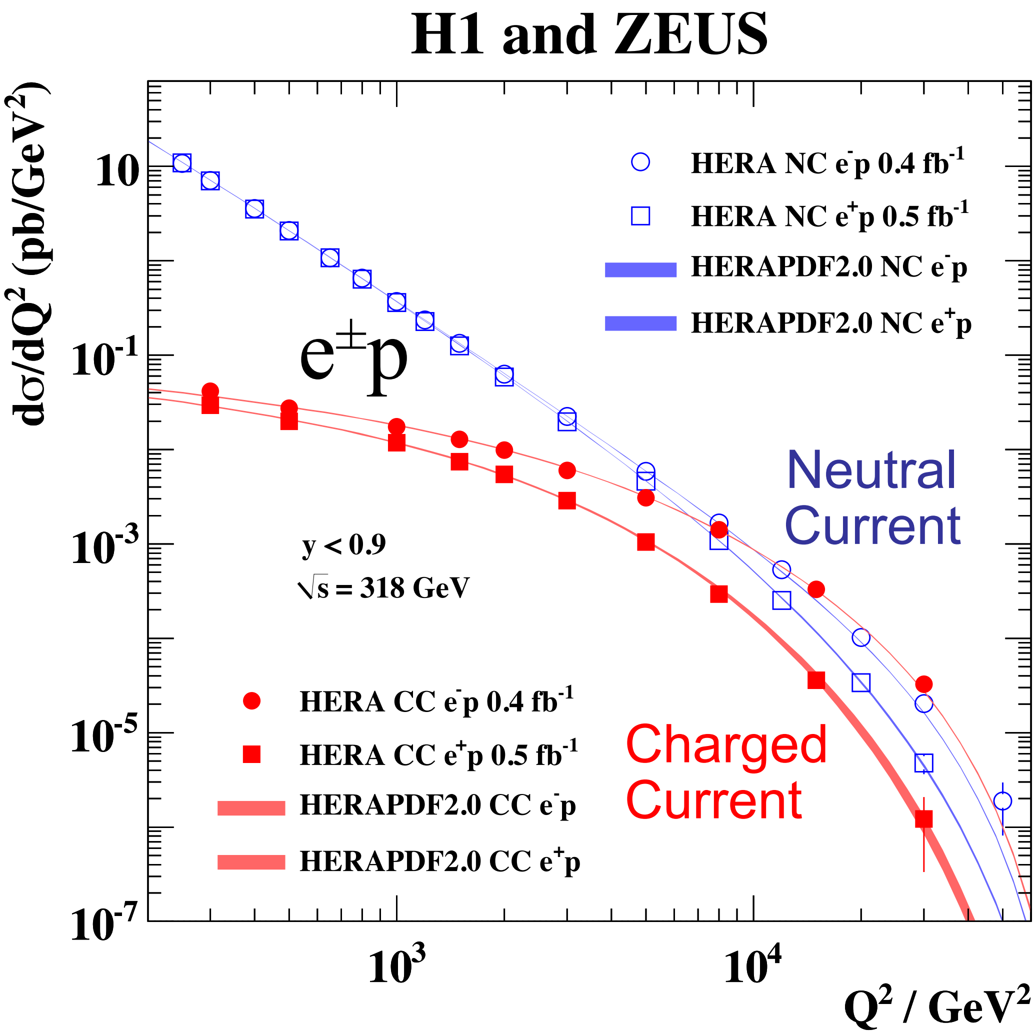
$\chi^2/d.o.f. = 1685/1620$

Checks in different corners of the phase space are in agreement with expected one sigma gaussian distributions of pulls.

Pulls are defined as

$$p^{i,k} = \frac{\mu^{i,k} - \mu^i \left(1 - \sum_j \gamma_j^{i,k} b'_j\right)}{\sqrt{\Delta_{i,k}^2 - \Delta_i^2}}$$

Combined NC and CC $e^{\pm}p$ data

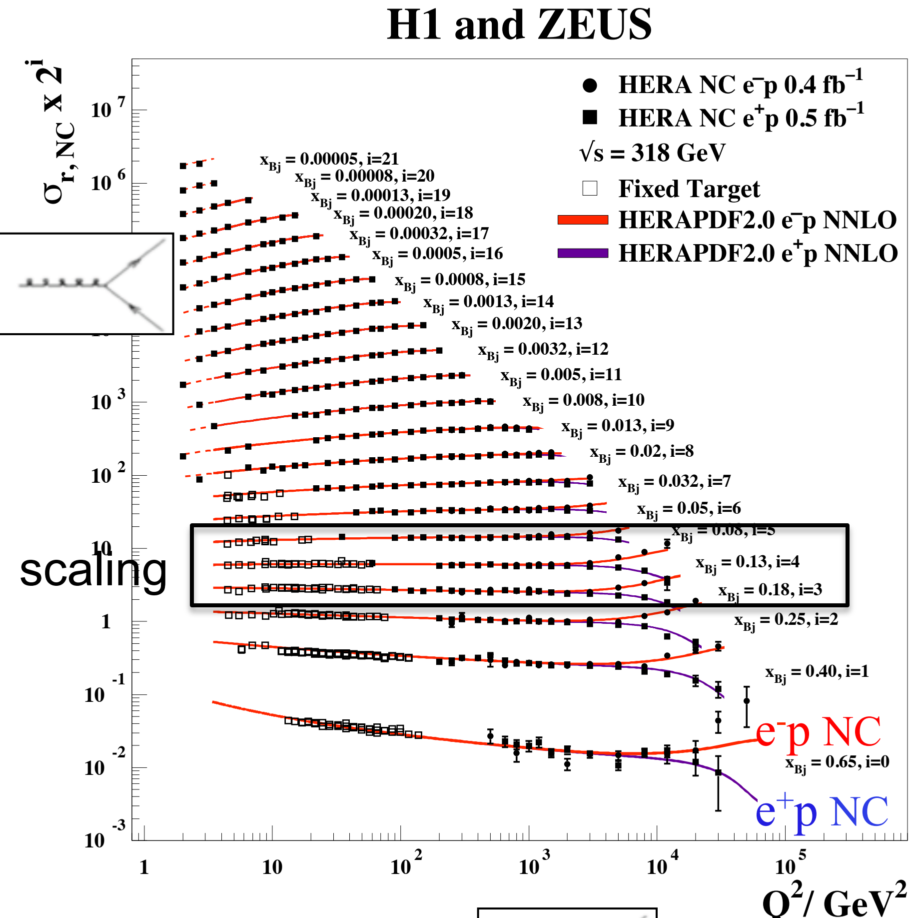


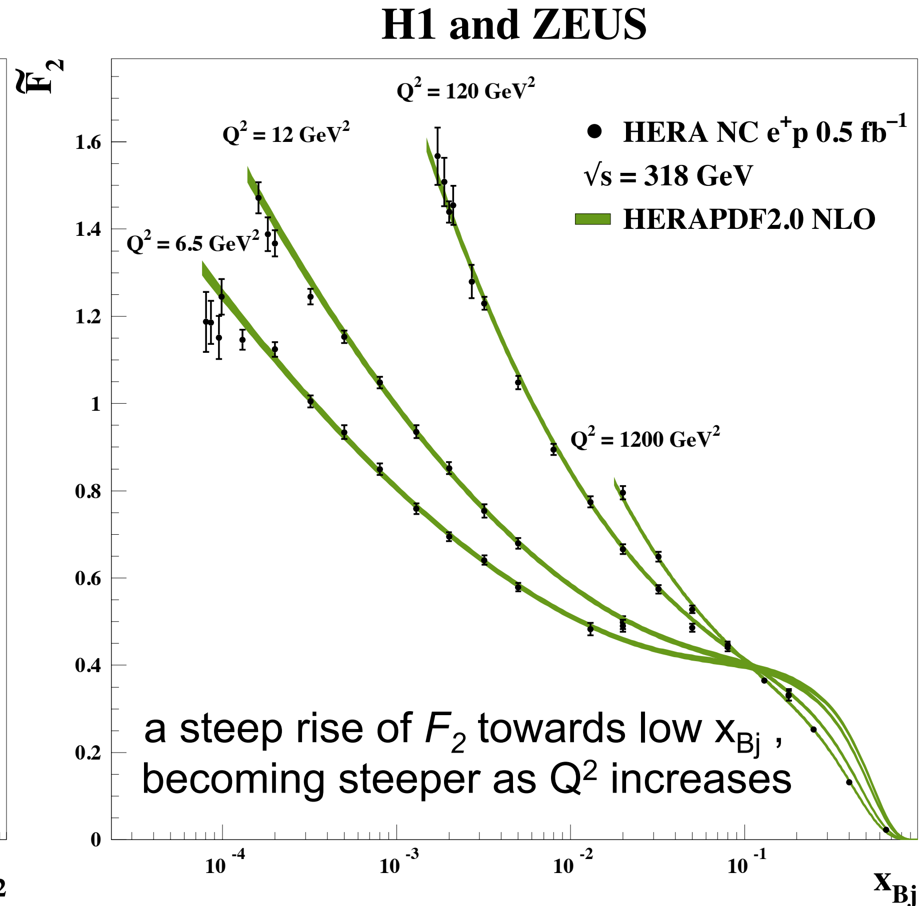
- single differential cross sections are obtained by integration over x of the combined NC and CC $e^{\pm}p$ data at $\sqrt{s}$=318 GeV and y<0.9
- e^+p NC and e^-p NC are the same in the γ-exchange domain at low Q^2 and start to differ at high Q^2 due to γZ interference.
- CC is two orders of magnitude smaller than NC at Q^2=200 GeV^2 and about the same at Q^2 around M_Z^2, M_W^2, demonstrating **electroweak unification.**
- remaining differences in CC are related to u, d content of the proton and to helicity factors.

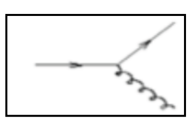
arxiv:1506.06042

Proton structure function F_2

F_2 scaling (independence of Q^2) at moderate x and scaling violations at high x_{Bj} and low x_{Bj} due to gluon emission and gluon splitting







arxiv:1506.06042

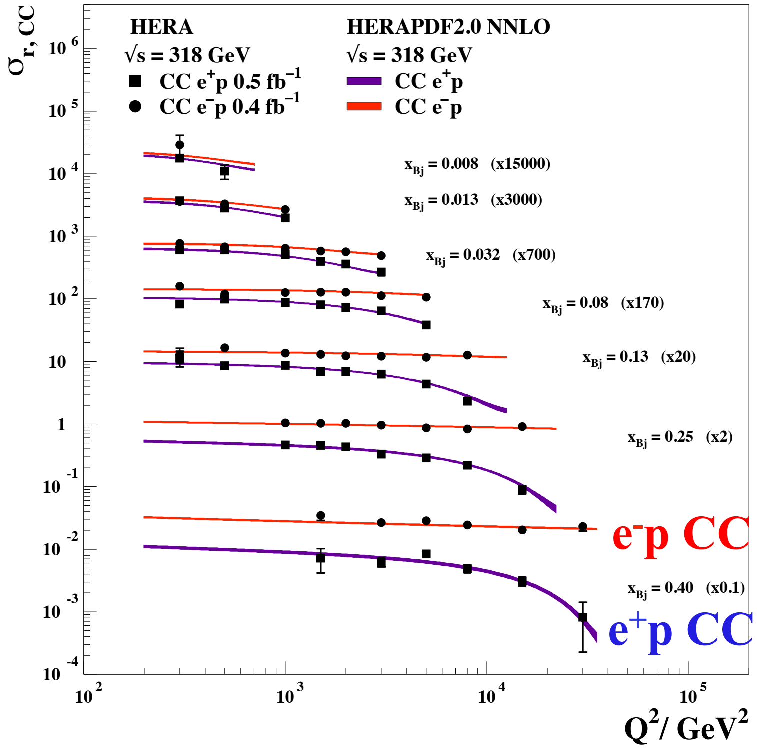
$e^{\pm}p$ CC probe u/d composition of proton

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

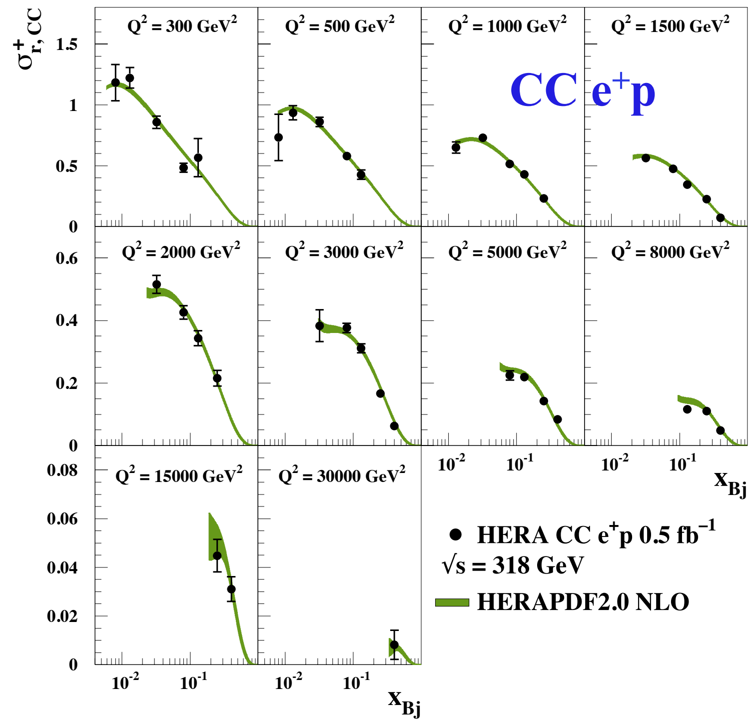
$$\tilde{\sigma}^{+}_{CC} \sim (x\bar{u} + x\bar{c}) + (1-y)^2(xd + xs)$$

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

H1 and ZEUS



H1 and ZEUS



e⁺p CC *at high x is related to* ***d-quark*** *(Q^2 dependence is due to helicity factor $(1-y)^2$)*

e⁻p CC *is dominated by* ***u-quark*** *and depends weakly on Q^2 at given x*

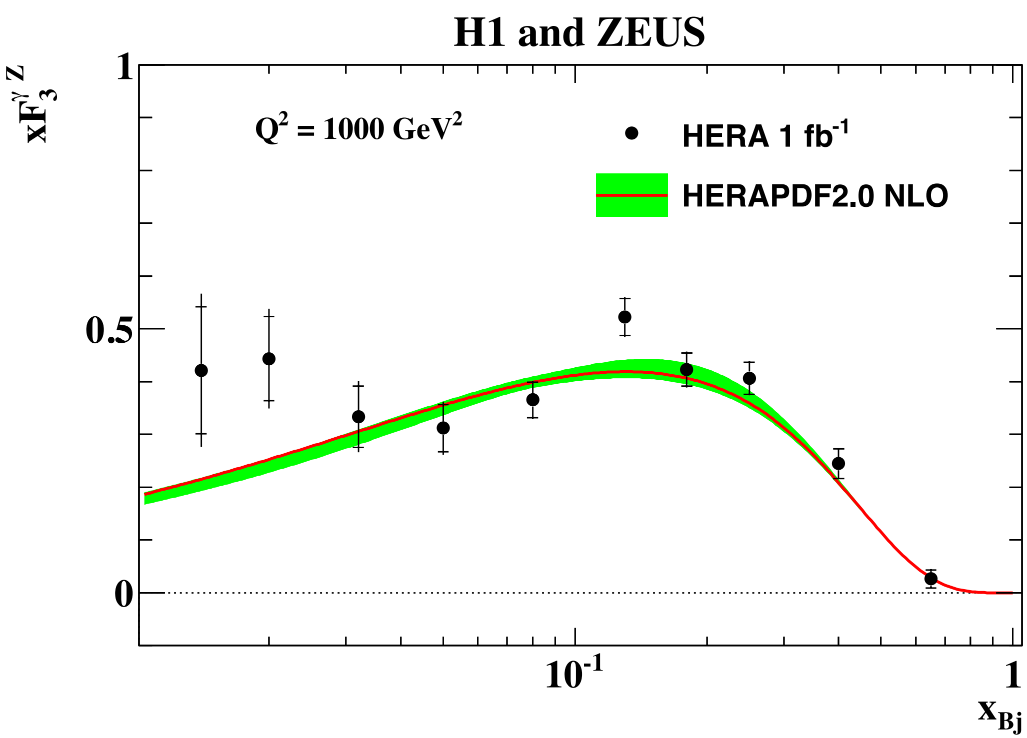
$e^{\pm}p$ NC: lepton charge dependence and xF_3

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

charge asymmetry of $e^{\pm}p$ NC cross sections is mostly due to γZ interference

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

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



transform the $xF_3^{\gamma Z}(x,Q^2)$ measurements to $Q^2 = 1000$ GeV^2 and average them to get $xF_3^{\gamma Z}(x)$ at $Q^2 = 1000$ GeV^2

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

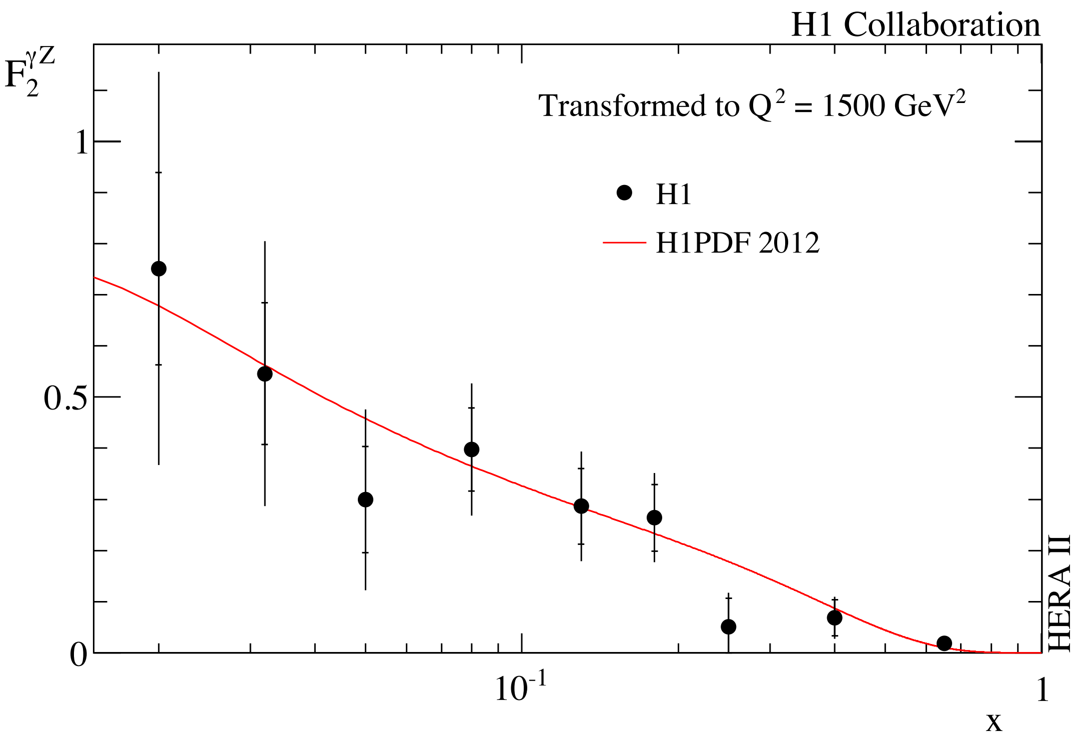
→ integration over the measured range $0.016 < x_{Bj}$ 0.725 gives 1.165+0.042-0.053 for data and 1.314±0.057(stat)±0.057(syst) using HERAPDF2.0

NC: The parity violating structure function $F_2^{\gamma Z}$

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

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

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



longitudinal polarisation of e-beam :
$\mathbf{P_e = (N_r - N_l)/(N_r + N_l)}$, where
$N_l(N_r)$ - number of left- (right-) handed leptons in e-beam

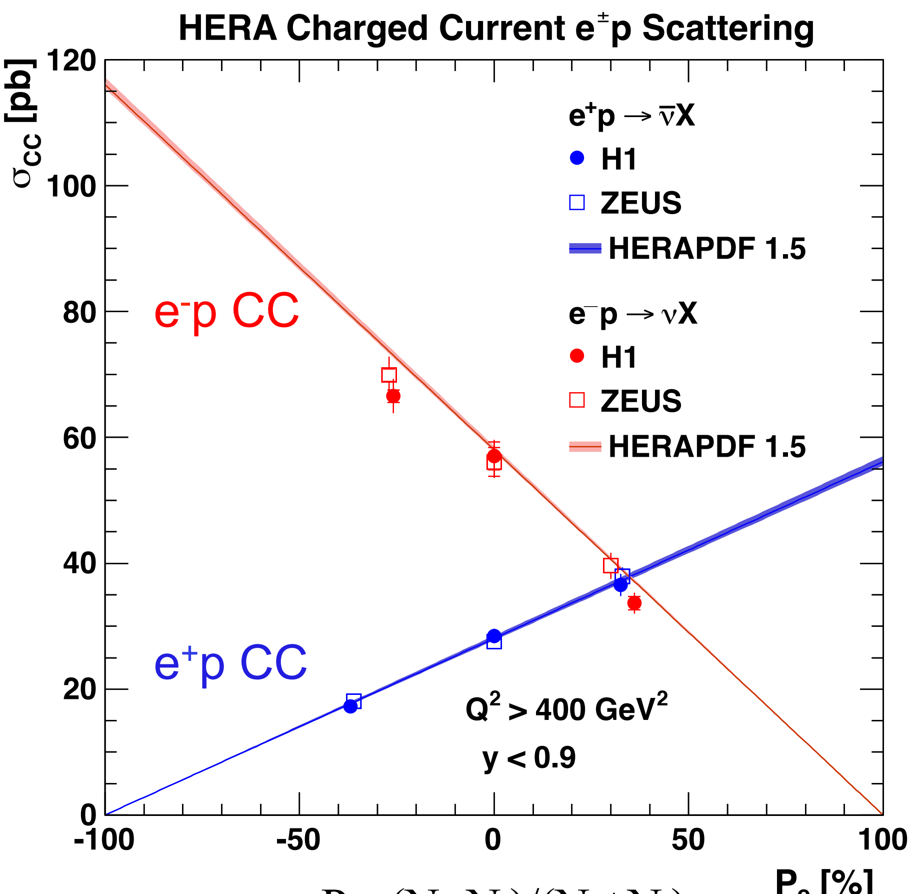
"left" and "right" data periods are with
$P_L = \langle P_e \rangle$ below zero (<0)
$P_R = \langle P_e \rangle$ above zero (>0)

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

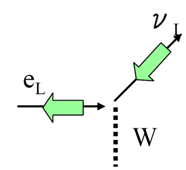
→ $F_2^{\gamma Z} = \sum 2e_q v_q(xq + x\bar{q})$

Probe (V-A) structure of CC

Polarisation dependence of the total CC cross section (Q^2>400 GeV^2, y<0.9)



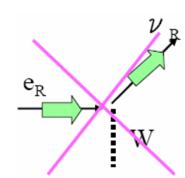
$P_e=(N_r-N_l)/(N_r+N_l)$



V-A structure of CC
(pure left-handed)

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

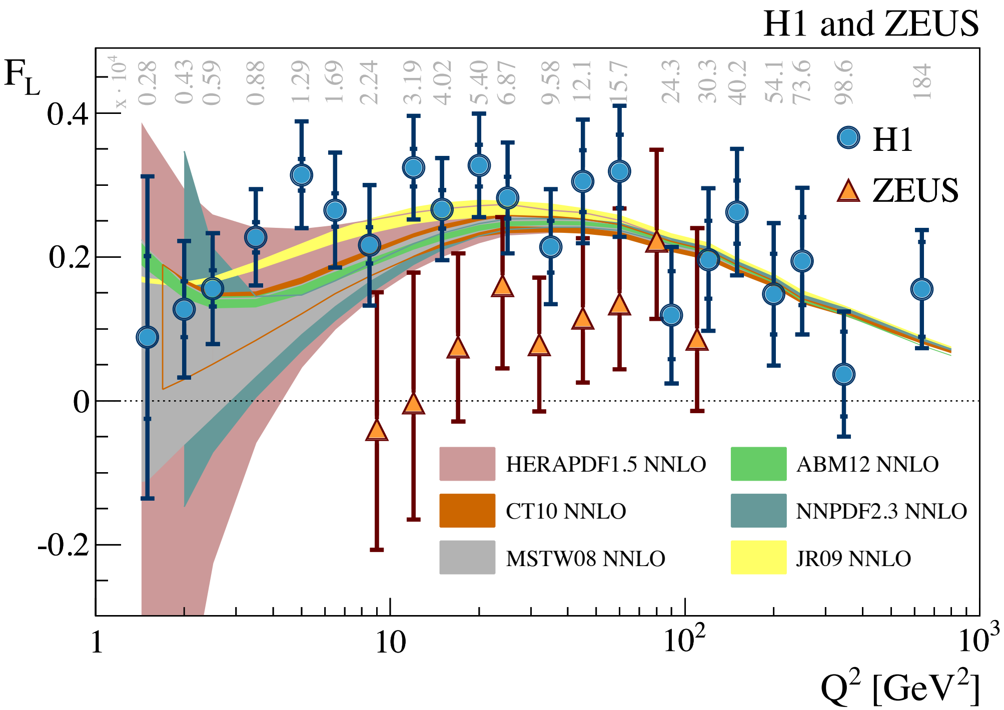
linear dependence with σ=0 intercept at P_e=1 for e^-p and P_e=-1 for e^+p



→ absence of right-handed weak currents

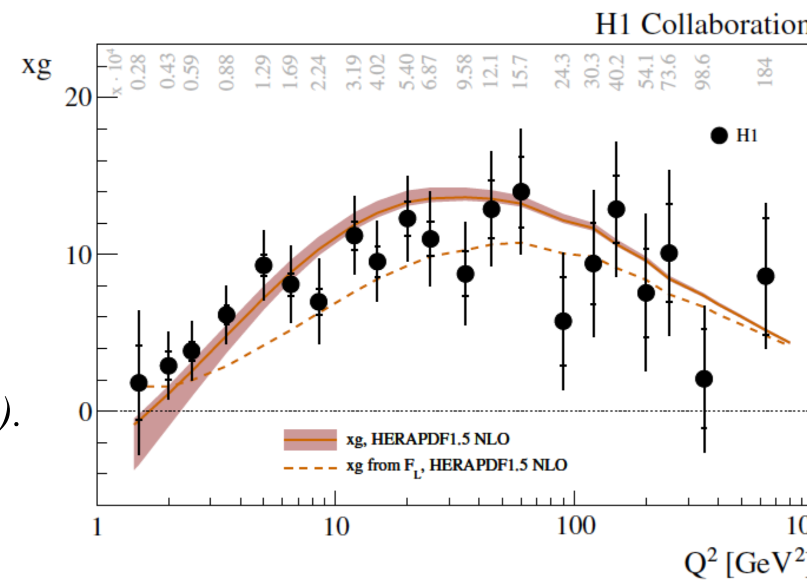
Longitudinal structure function F_L

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



approximate relation between F_L and gluon (order of α_s, with a=1)

$$xg(x,Q^2) \approx 1.77 \frac{3\pi}{2\alpha_S(Q^2)} F_L(ax,Q^2)$$



Consistency of the H1 and ZEUS F_L data was checked accounting for corr. errors: χ^2/d.o.f.=11/8 (p-value=20%).

$R=\sigma_L/\sigma_T=F_L/(F_2-F_L)$ = 0.23±0.04 (H1, $1.5 \le Q^2 \le 800$ GeV^2)
R=0.105+0.055-0.037 (ZEUS, $9 \le Q^2 \le 110$ GeV^2)

HERAPDF2.0 QCD Fit

The combined $e^{\pm}p$ NC/CC HERA data set is the only input

- no nuclear, heavy target or HT corrections; consistency of data, $\Delta\chi^2 = 1$ criterion
- parametrisation of PDFs at starting scale Q_o^2=1.9 GeV^2 with 14 free parameters

$$xg(x) = A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g},$$

$$xu_v(x) = A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1+E_{u_v}x^2\right), \qquad x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}\,(1+D_{\bar{U}}x)\,,$$

$$xd_v(x) = A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}, \qquad x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.$$

- QCD evolution of PDFs using DGLAP equations at NLO and NNLO
- Thorne-Roberts general mass variable-flavor-number scheme RTOPT (as used in MMHT)
- default Q^2_{min}=3.5 GeV^2, f_s=0.40 ($x\bar{s} = f_s\, x\bar{D}$ at Q_o^2)
- M_c and M_b values are optimized using HERA charm and beauty production data
- $\alpha_s(M^2_Z)$=0.118 is consistent with HERA jet data

→ available at www.desy.de/h1zeus/herapdf20/ and will be available on LHAPDF:

HERAPDF2.0 at NLO and NNLO
also with a scan of $\alpha_s(M^2_Z)$ from 0.110 to 0.130 in steps of 0.001

additional PDF sets :
- HERAPDF2.0HiQ2 at NLO and NNLO - Q^2_{min}=10 GeV^2
- HERAPDF2.0AG at LO, NLO and NNLO - alternative gluon parameterisation (strictly positive)
- HERAPDF2.0FF3A and FF3B - fixed flavor number schemes at NLO

Uncertainties of HERAPDF2.0

Three types of PDF uncertainties are considered:

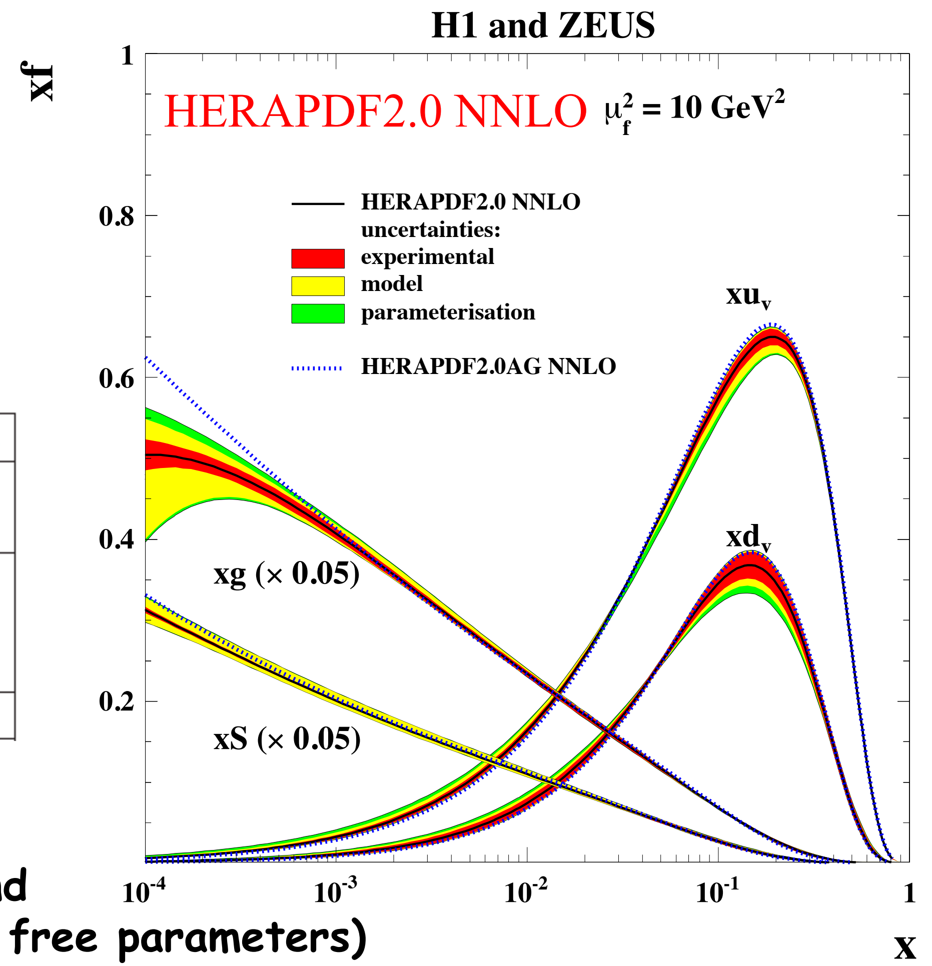
Experimental uncertainty band

- **Hessian method with $\Delta\chi^2 = 1$**
verifyed by MC method - replicas of data

Model uncertainty band

- **variation of model assumptions**

Variation	Standard Value	Lower Limit	Upper Limit
Q^2_{min} [GeV^2]	3.5	2.5	5.0
Q^2_{min} [GeV^2] HiQ2	10.0	7.5	12.5
M_c(NLO) [GeV]	1.47	1.41	1.53
M_c (NNLO) [GeV]	1.43	1.37	1.49
M_b [GeV]	4.5	4.25	4.75
f_s	0.4	0.3	0.5



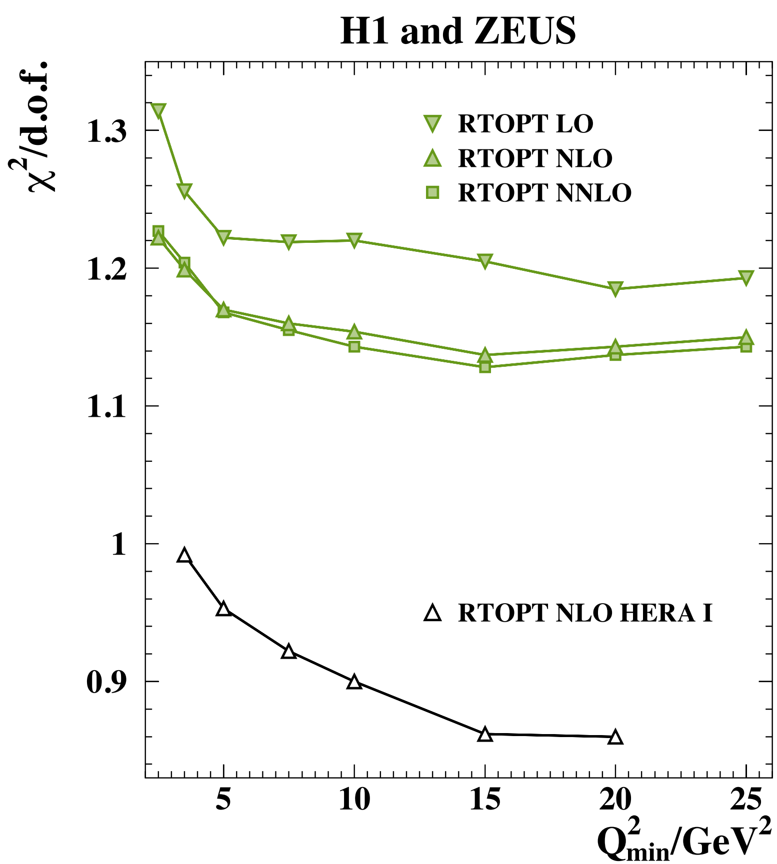
Parameterisation uncertainty band

- **variation of the starting scale Q_o^2 and**
- **form of parameterisation (number of free parameters)**

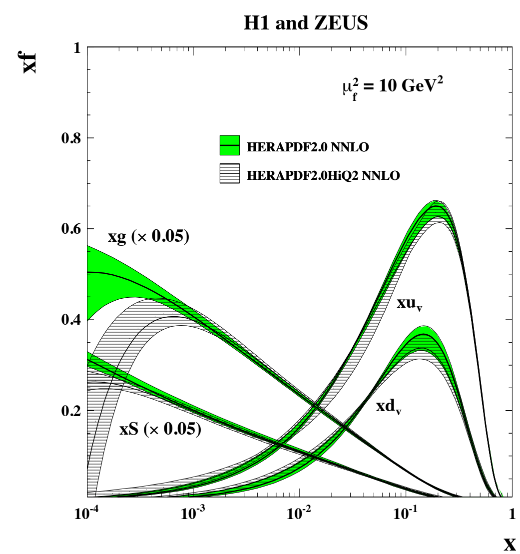
→ *valid in the x-range covered by the QCD fit to HERA data*

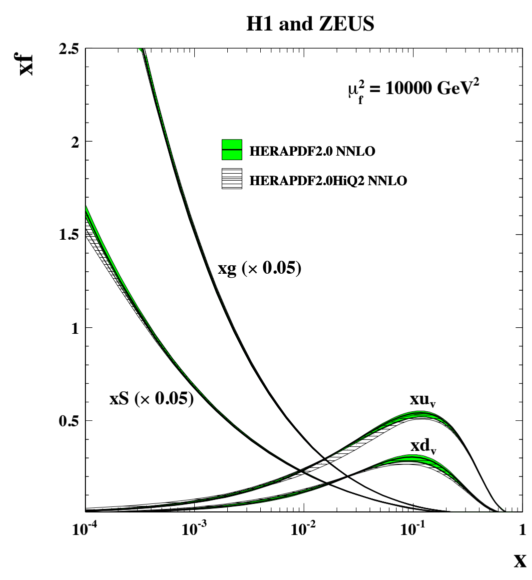
HERAPDF2.0 dependence on Q^2_{min}

χ^2/d.o.f. is improving from 1.20 to 1.15 with increasing Q^2_{min} from 3.5 to 10 GeV^2
(similar behavior was for HERAPDF1.0 although at smaller values of χ^2/d.o.f.)



HERAPDF2.0HiQ2 is very similar to HERAPDF2.0 apart from low x measured at low $Q^2 < 10$ GeV^2

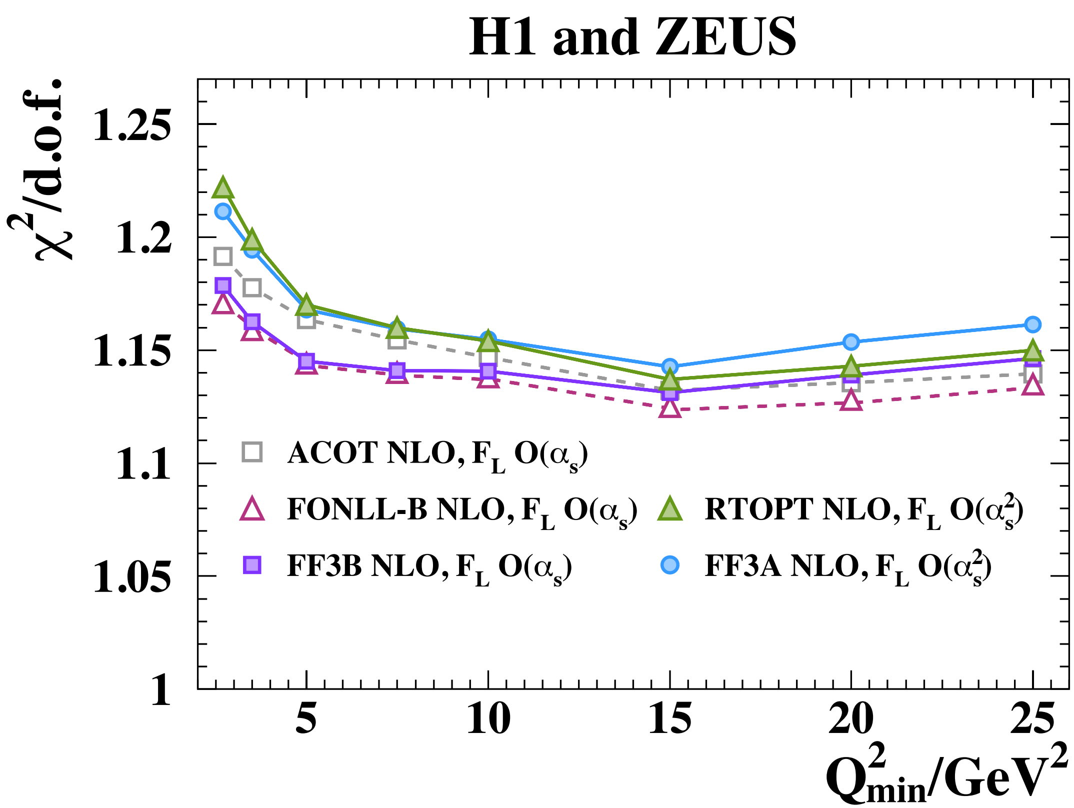




→ *this difference plays no role at large scales, for example at LHC*

Low Q^2 (and x) domain and F_L description

low Q^2 / low x domain (with increased χ^2/d.o.f.) is very interesting for study of low x phenomenology



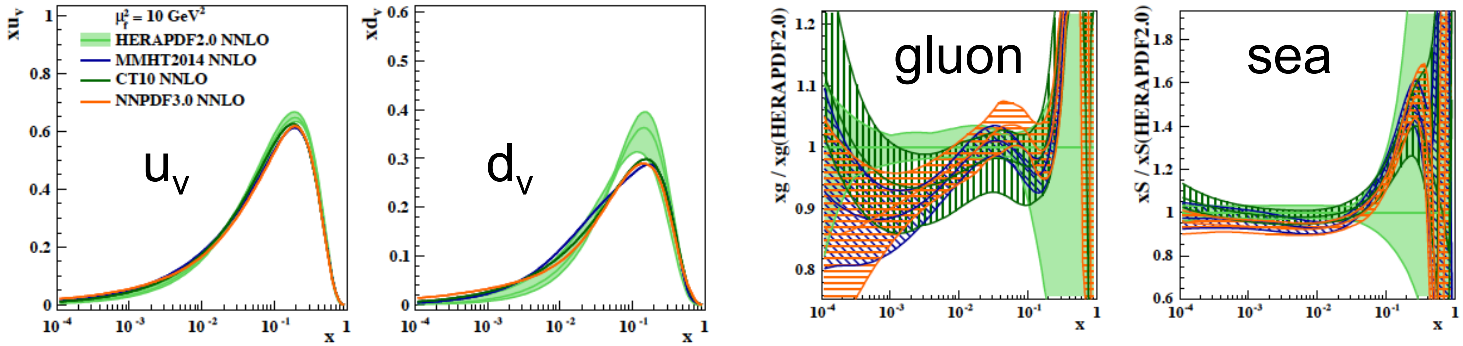
it seems that in this domain the order of the F_L calculation is more important then other QCD fit settings:

→ order of $O(a_s)$ is preferred

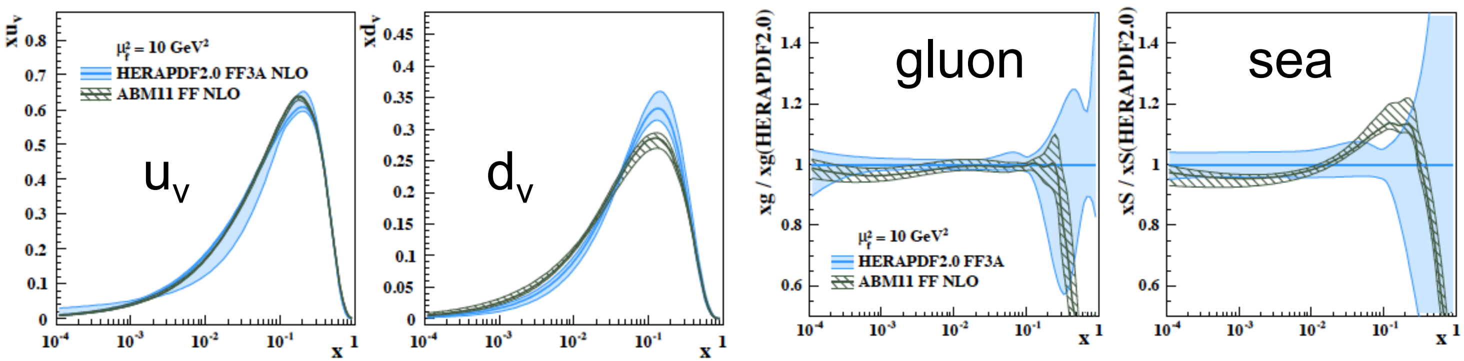
arxiv:1506.06042

Comparison with modern PDFs from global fits

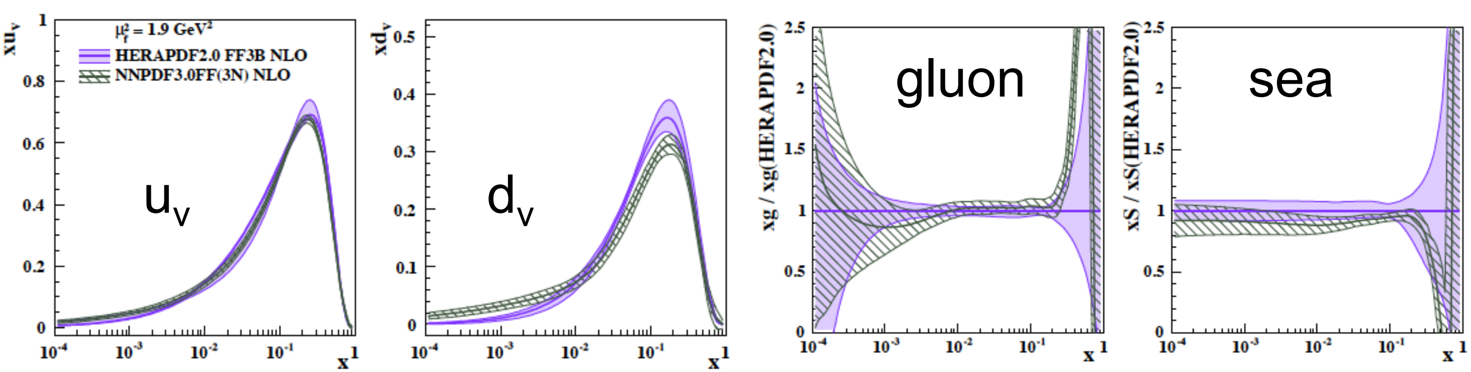
vs. PDFs using variable-flavor-number scheme: MMHT2014, CT10, NNPDF3.0



vs. PDFs using fixed-flavor-number scheme: ABM11 FF, NNPDF3.0FF(3N)



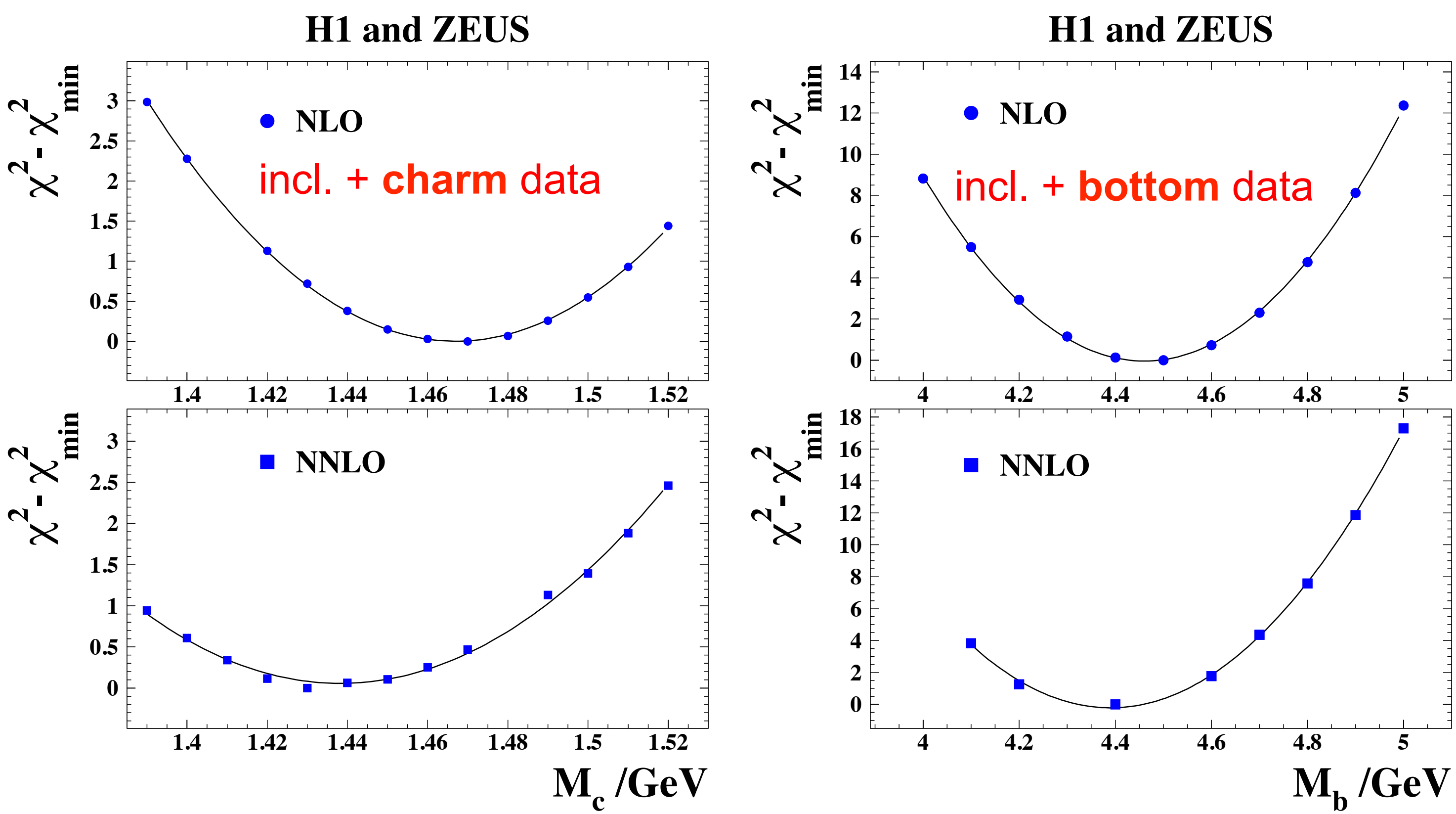
→ *differences in valence quarks at high x: new HERA data*



→ *sea and gluon are consistent*

Charm and botton mass parameters in HERAPDF2.0

M_c and M_b, charm and bottom mass parameters, are determined in χ^2 scans of the HERA charm and bottom data together with combined inclusive data



M_c = 1.47 (1.43) GeV at NLO (NNLO) M_b = 4.5 GeV at NLO, NNLO

→ ***reduction of the M_c and M_b uncertainties in HERAPDF fits***

arxiv:1506.06042

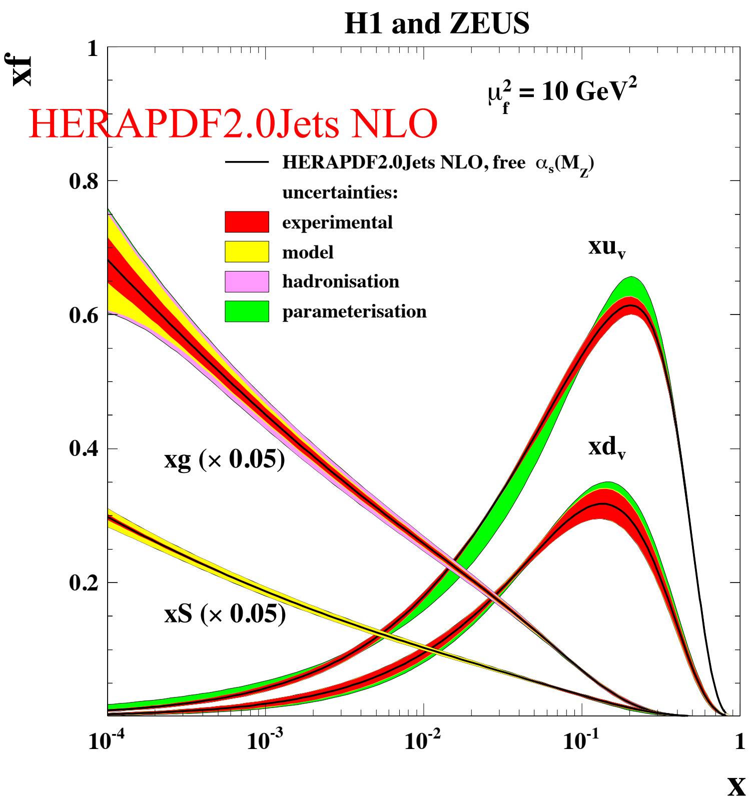
HERAPDF2.0Jets (inclusive + charm + jets)

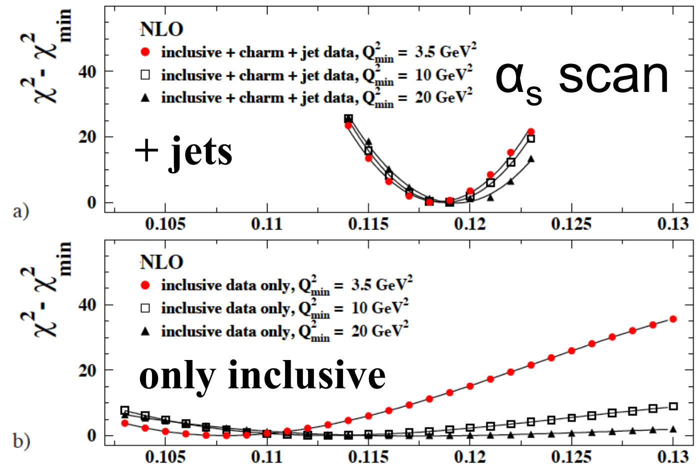
include also HERA combined charm production and selected jet production data :

at NLO, with free α_s and additional error band related to hadronisation of jets

→ *α_s , determined in a simultaneous fit with PDFs:*

$$\alpha_s(M^2_Z) = 0.1183 \pm 0.0009(exp) \pm 0.0005(model/param) \pm 0.0012(hadronisation)\ ^{+37}_{-30}(scale)$$





PDFs and the error bands are very close to HERAPDF2.0 obtained using inclusive data and M_c and M_b already optimized using charm and bottom HERA data and α_s=0.118, consistent with the HERA multi-jet data. (slight increase of err. band is due to hadronisation).

Conclusions

H1 and ZEUS completed the inclusive DIS program at HERA by combining all inclusive unpolarised measurements into one coherent data set of

NC & CC e^+p&e^-p at $\sqrt{s}$ = 319, 302, 251 and 225 GeV

with 169 common correlated systematic errors.

All three proton structure functions F_2, $F_2^{\gamma Z}$, $xF_3^{\gamma Z}$ and F_L are measured exploiting charge and polarity dependencies of the cross section measurements at HERA

This combined inclusive HERA data set of the NC and CC cross sections is used as a sole input to the QCD analysis of the data resulting in the set of parton distribution functions HERAPDF2.0 which will be available on LHAPDF together with its variants.