XXIII International Baldin Seminar on High Energy Physics Problems

September 19 – 24, 2016, Dubna, Russia

Proton Structure Functions and Parton Densities at HERA

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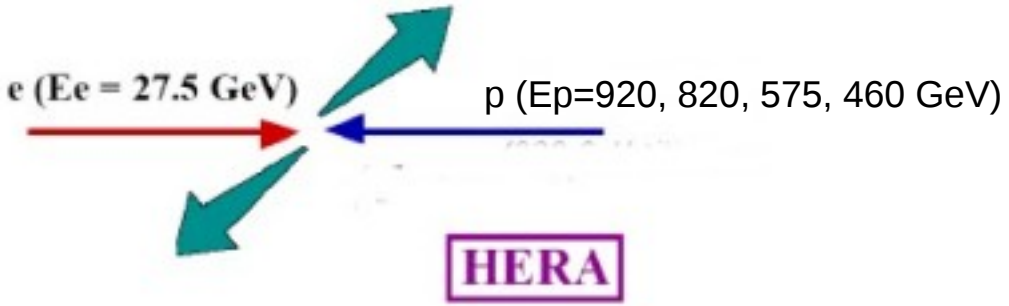
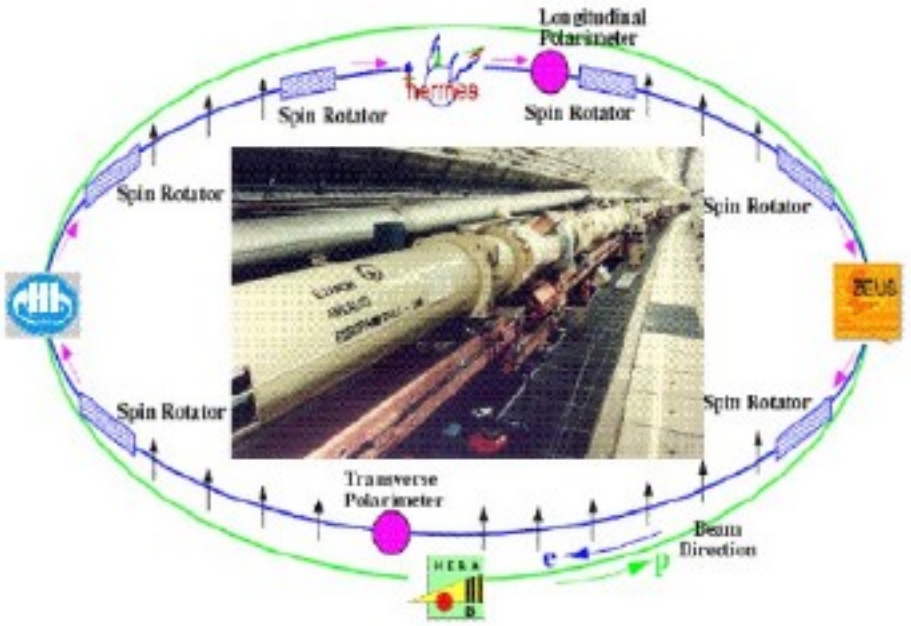
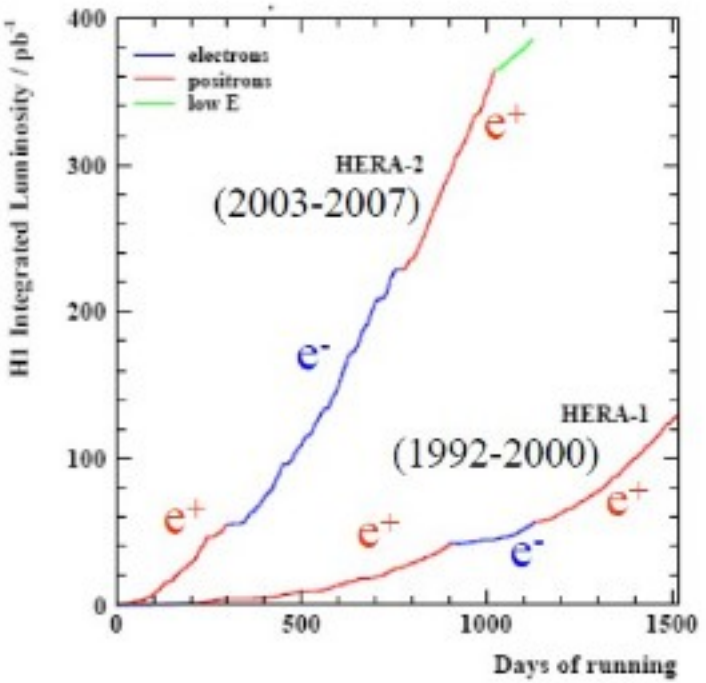
Eur.Phys.J.C75 (2015) 12, 580 [arxiv:1506.06042]
Eur.Phys.J.C 74 (2014) 2814 [arxiv:1312.4821]
Phys. Rev. D 90 (2014) 072002 [arXiv:1404.6376]

The HERA collider





H1 and ZEUS
0.5 fb^{-1} per experiment
e^+ and e^-

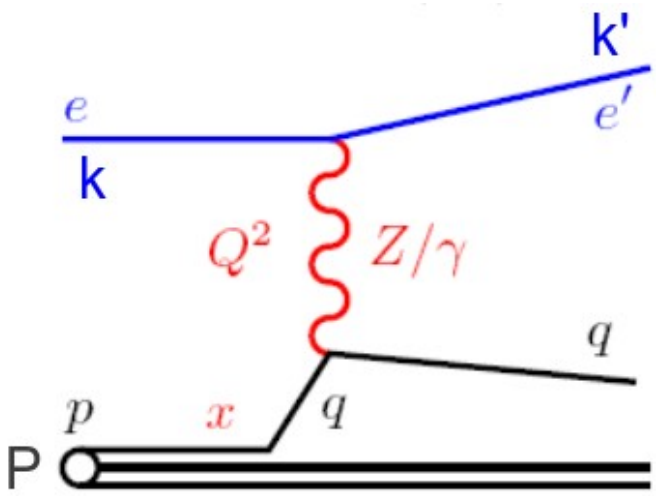


$Q^2_{max} \sim 10^5$ GeV^2

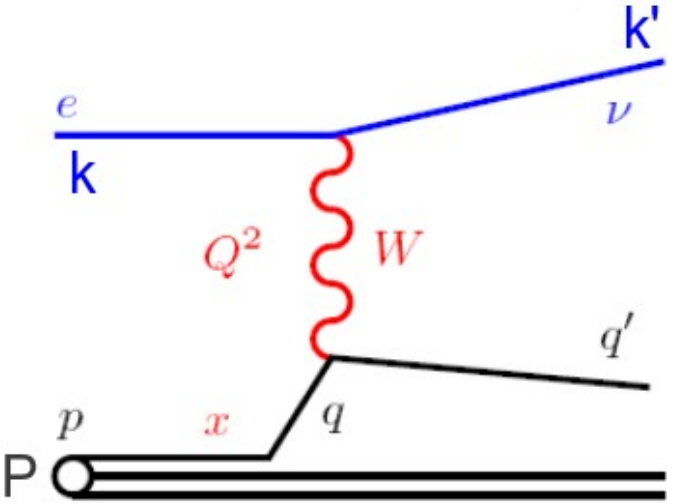
$\lambda_{min} \sim R_{proton} / 1000$

Deep Inelstic Scattering (DIS)

Neutral Current (NC)



Charged Current (CC)



$$s = (k + P)^2$$ centre-of-mass energy squared

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

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

$$y = \frac{(Pq)}{(Pk)}$$ inelasticity

realted as $Q^2 = sxy$

Charged Current Cross Section

reduced cross section

cross section measurement

structure fuctions

$$\sigma^{\pm}_{r,CC} = \frac{2\pi x}{G_F^2}\left[\frac{M_W^2+Q^2}{M_W^2}\right]^2 \cdot \frac{d^2\sigma^{e\pm p}_{CC}}{dxdQ^2} = \frac{Y_+}{2}W_2^{\pm} \mp \frac{Y_-}{2}xW_3^{\pm} - \frac{y^2}{2}W_L^{\pm}$$

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

In QPM

$$W_2^- = x(u + c + \bar{d} + \bar{s}) \quad xW_3^- = x(u + c - \bar{d} - \bar{s})$$

$$W_2^+ = x(\bar{u} + \bar{c} + d + s) \quad xW_3^+ = x(d + s - \bar{u} - \bar{c})$$

Neutral Current Cross Section

$$\sigma^{\pm}_{r,NC} = \frac{d^2\sigma^{e\pm p}_{NC}}{dxdQ^2} \cdot \frac{xQ^4}{2\pi\alpha^2 Y_+} = \tilde{F}_2 \mp \frac{Y_-}{Y_+} x\tilde{F}_3 - \frac{y^2}{Y_+}\tilde{F}_L$$

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

$$\tilde{F}_2 = F_2 - \kappa_Z v_e \cdot F_2^{\gamma Z} + \kappa_Z^2(v^2 + a_e^2) \cdot F_2^Z$$

$$\tilde{F}_L = F_L - \kappa_Z v_e \cdot F_L^{\gamma Z} + \kappa_Z^2(v^2 + a_e^2) \cdot F_L^Z$$

$$x\tilde{F}_3 = -\kappa_Z a_e \cdot xF_3^{\gamma Z} + \kappa_Z^2 \cdot 2v_e a_e \cdot xF_3^Z$$

$$\kappa_Z(Q^2) = \frac{Q^2}{Q^2 + M_Z^2} \cdot \frac{1}{4\sin^2\theta_W \cos^2\theta_W}$$

In QPM

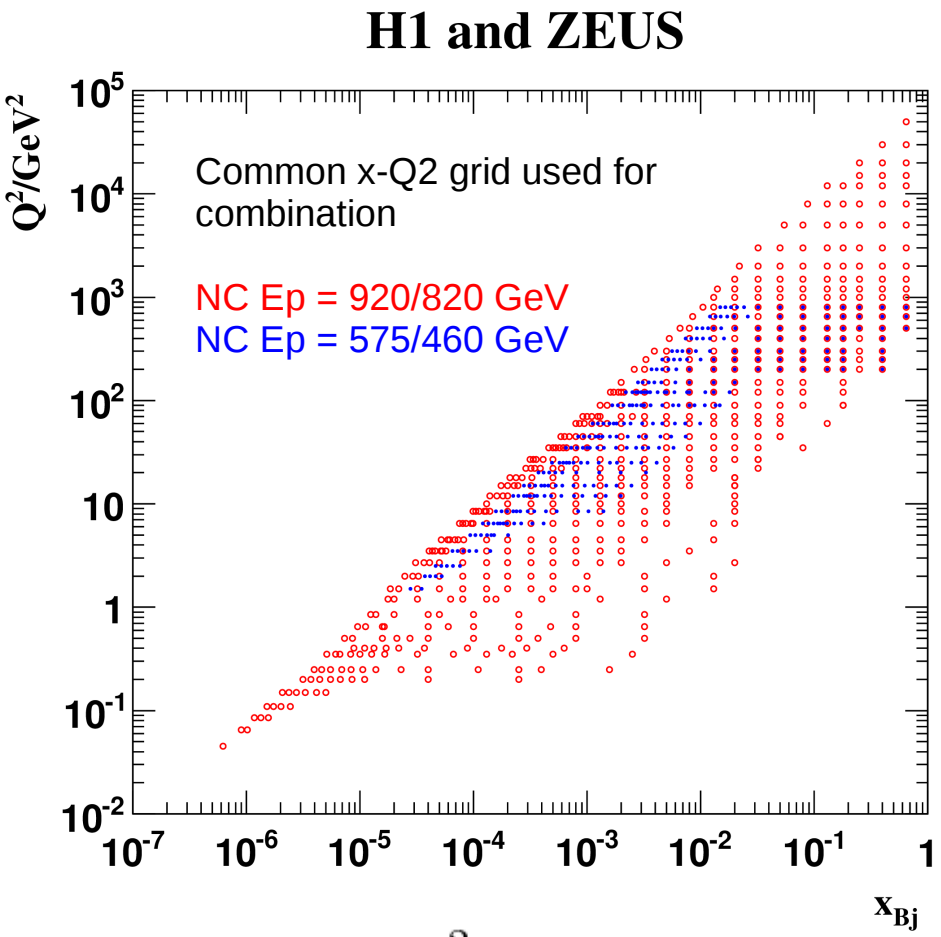
$$[F_2, F_2^{\gamma Z}, F_2^Z] = x\sum [e_q^2, 2e_q v_q, v_q^2 + a_q^2](q + \bar{q})$$

$$[xF_3^{\gamma Z}, xF_3^Z] = 2x\sum_q [e_q a_q, v_q a_q](q - \bar{q})$$

The QCD lowest order in α_s

$$F_L = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3}\left[\frac{16}{3}F_2 + 8\sum_q e_q^2(1 - \frac{x}{z}) \cdot xg\right]$$

NC and CC Inclusive Data Samples



$$0.045 \leq Q^2 \leq 50000 \text{ GeV}^2$$

$$6 \cdot 10^{-7} \leq x \leq 0.65$$

41 NC and CC data samples from H1 and ZEUS experiments

- 21 data sets from HERA I
- 20 data sets from HERA II

Corresponding lumi is about 1 fb^{-1}

Combine data properly taking uncertainties into account

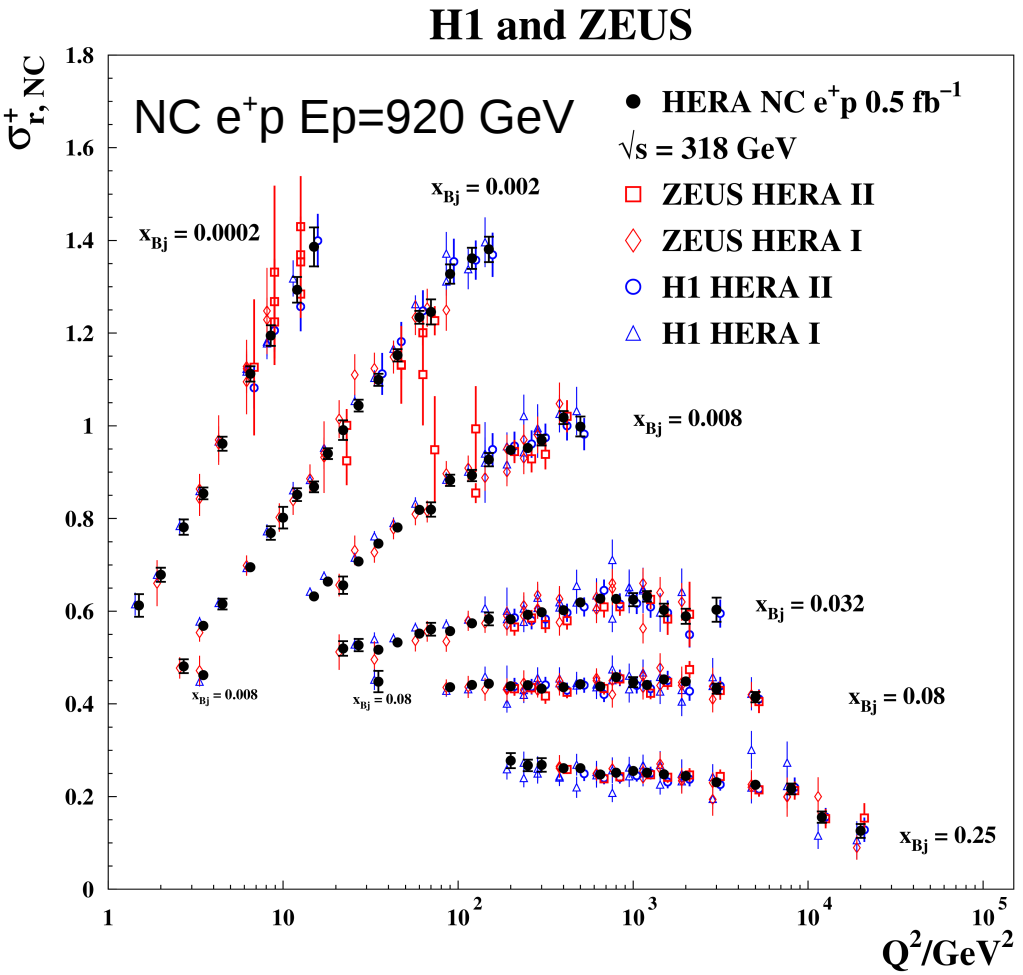
- procedure is the same as was used for HERA I before

Averaging cross section

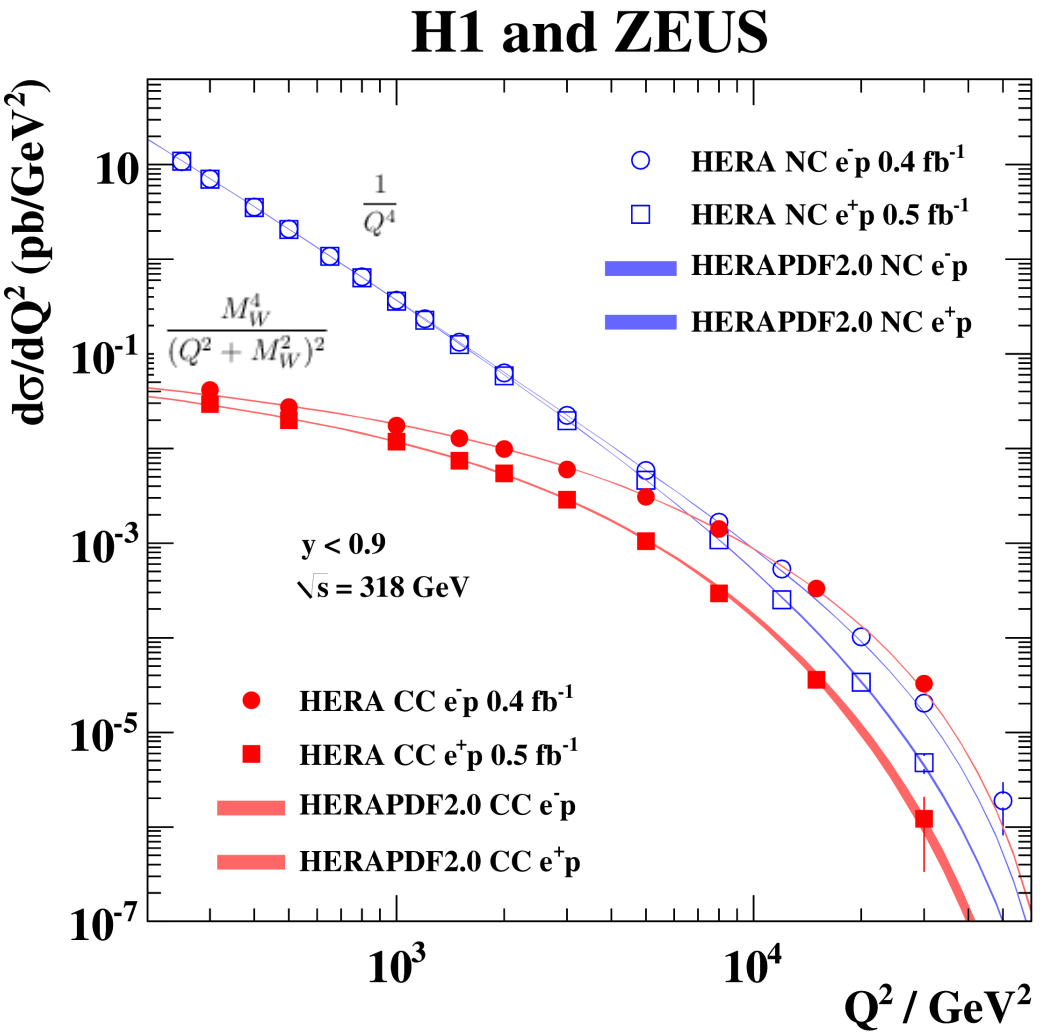
2927 cross sections are combined into 1307 points with 169 correlated systematic errors
χ^2 / ndf = 1685/1620

Combination of up to 6 measurements into one averaged point

Reduction of stat. and syst. uncertainties



NC and CC DIS Cross Section



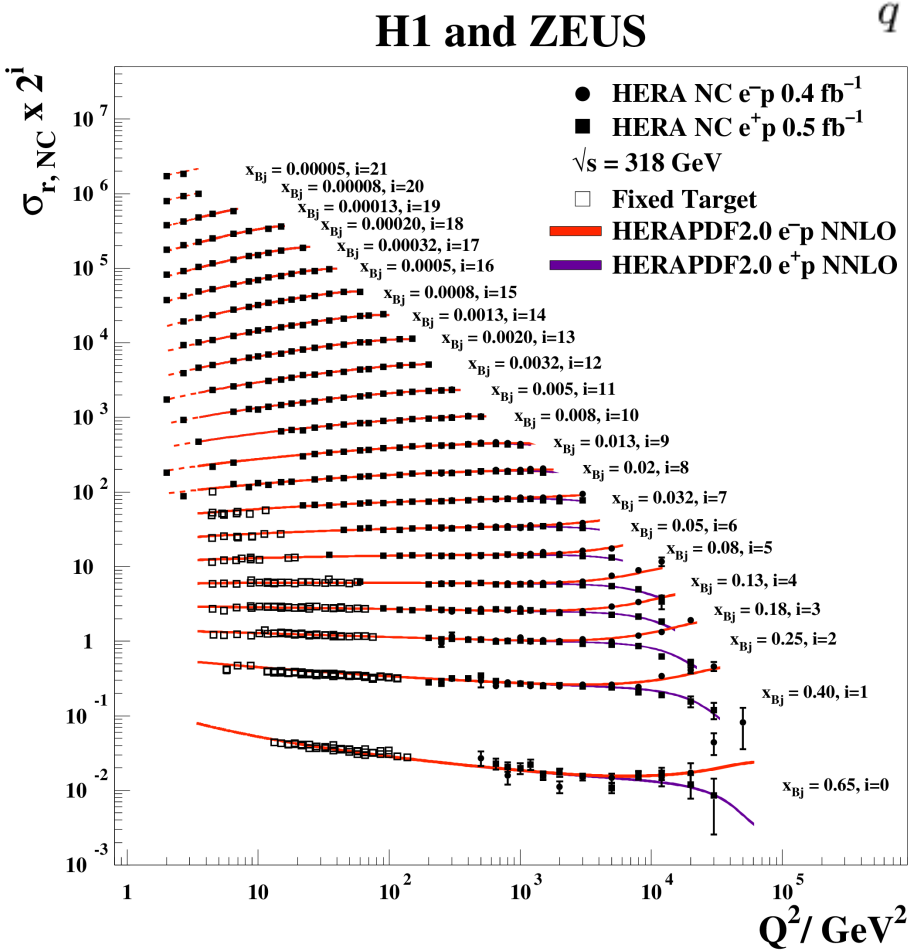
EW component of SM

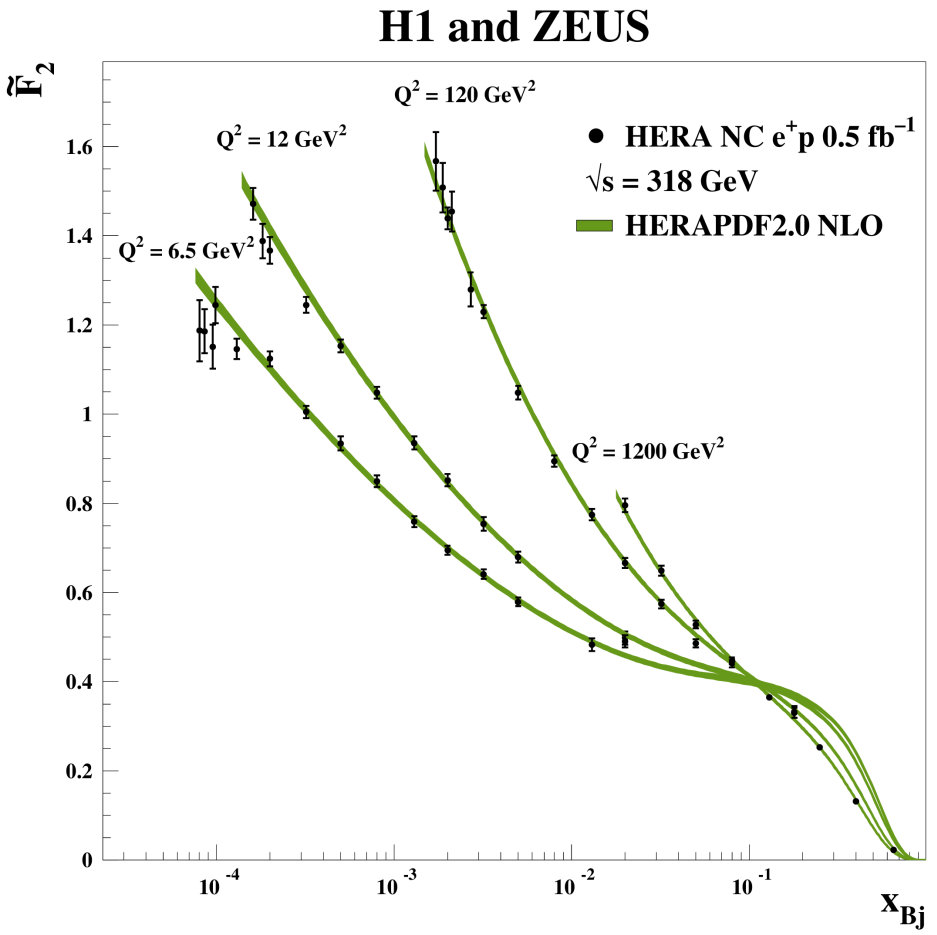
NC and CC cross sections become similar at $Q^2 \approx M_Z^2, M_W^2$

Demonstration of electroweak unification

F_2 Structure Function

The main contribution $\tilde{F}_2 \approx \sum_q e_q^2 (q + \bar{q})$



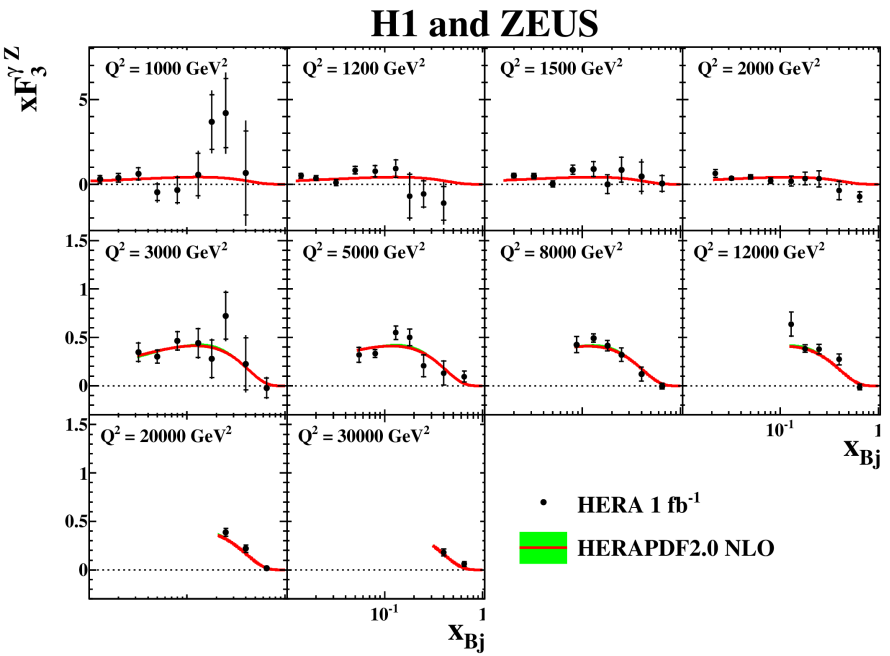


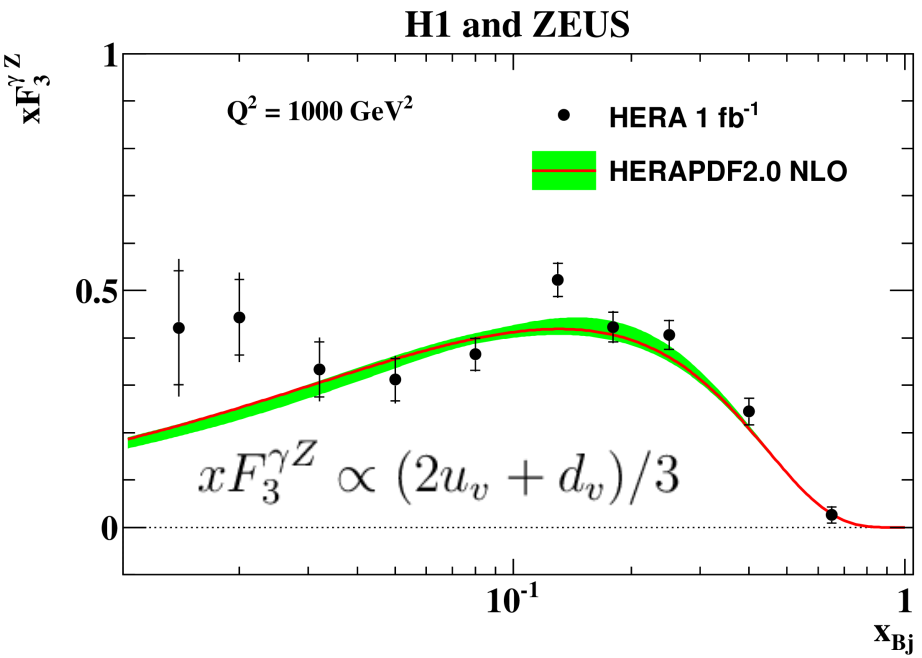
Interplay between gluon emission and gluon splittng results in F_2 scaling at x ~ 0.1

xF_3 Structure Fuction

At high Q^2 $\sigma^{\pm}_{r,NC} \approx \tilde{F}_2 \pm \frac{Y_-}{Y_+} x\tilde{F}_3$

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





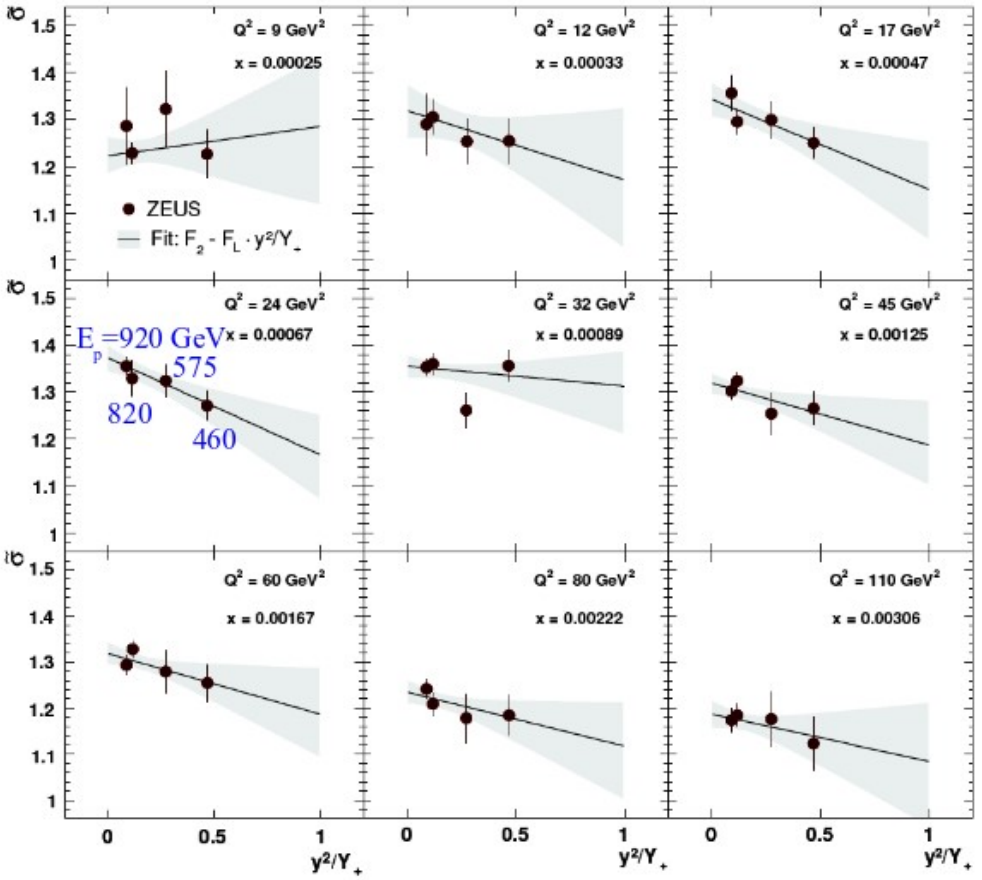
$$xF_3^{\gamma Z} = -x\tilde{F}_3(Q^2 + M_Z^2)/(a_e k Q^2) \qquad k^{-1} = 4\frac{M_W^2}{M_Z^2}\left(1 - \frac{M_W^2}{M_Z^2}\right)$$

Effect is mostly from from yZ interference

Little Q^2 dependence, so transform all to the same Q^2 = 1000 GeV^2 and average

F_L Structure Function: Linear Fit

At moderate Q^2 $$\sigma_{r,NC}(x, Q^2, y) \approx \tilde{F}_2(x, Q^2) - \frac{y^2}{Y_+}\tilde{F}_L(x, Q^2)$$



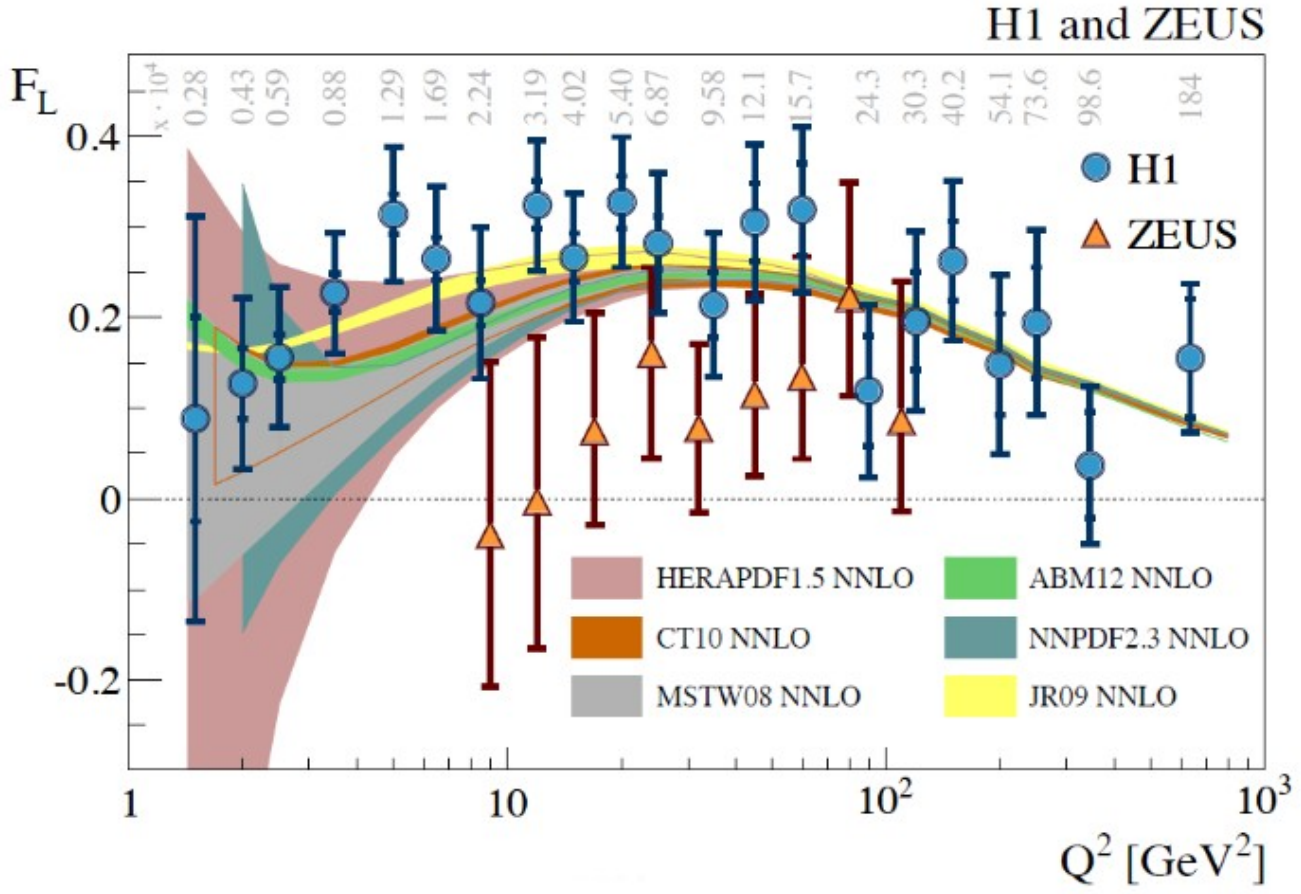
Sensitivity to F_L at high y only

Change s at fixed x and Q^2 → change y

Simultaneous extraction of F_L and F_2 with the linear fit

Results are model independent

The Longitudinal Structure Function $F_L(Q^2)$

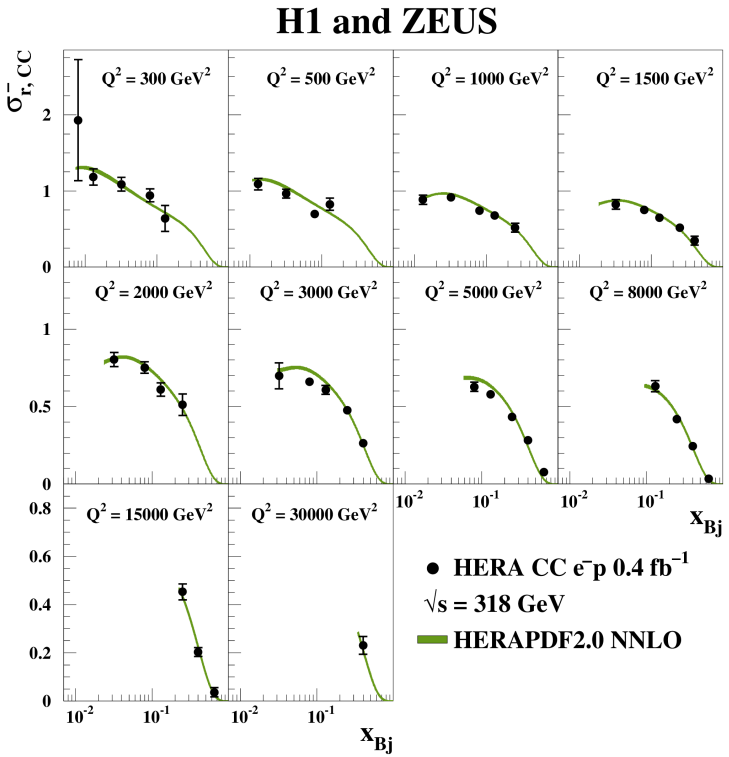


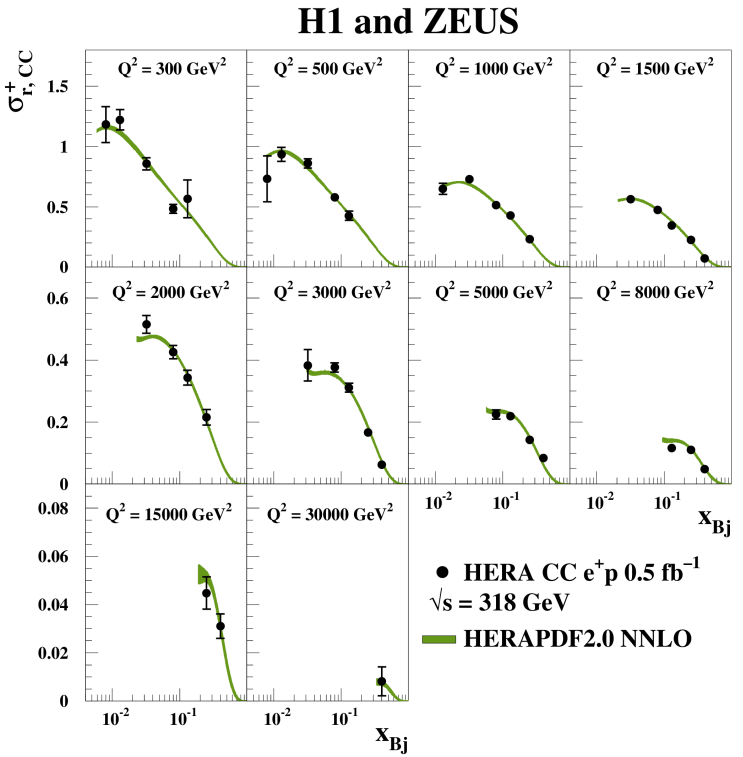
Probability of agreement is about 20%
Good agreement between NNLO predictions and the measurement
Additional constraints to PDF's at low Q^2

CC probe of u/d decompositon of proton

$$\tilde{\sigma}(e^- p) \propto (xu + xc) + (1-y)^2(x\bar{d} + x\bar{s})$$

$$\tilde{\sigma}(e^+ p) \propto (x\bar{u} + x\bar{c}) + (1-y)^2(xd + xs)$$





e^-p is dominated by u-quark

e^+p at high x is related to d-quark

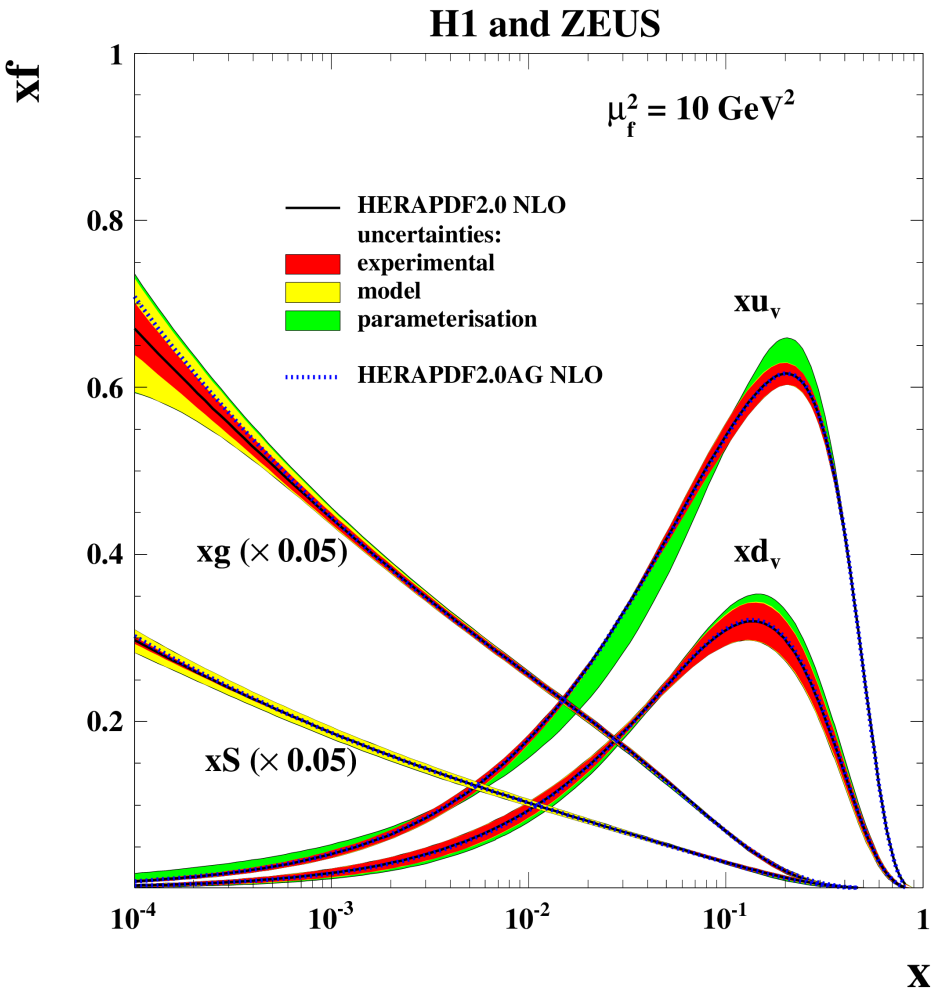
HERAPDF2.0 QCD Fit

- PDFs DGLAP evolution at NLO and NNLO
- Input: HERA combined NC/CC data sets
- No nuclear, heavy target corrections
- Starting scale: $Q^2_0 = 1.9\ \mathrm{GeV}^2$
- Parametrization

$$xg(x) = A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g}$$
$$xu_v(x) = A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}(1+E_{u_v}x^2)$$
$$xd_v(x) = A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}$$
$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}(1+D_{\bar{U}}x)$$
$$x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{D_{\bar{D}}}$$

- Heavy quarks: general-mass variable-flavour-number scheme RTOPT
- Available at www.desy.de/h1zeus/herapdf20/ and on LHAPDF

HERAPDF2.0 : Uncertainties



Experimental uncertainty

Hessian method with $\Delta\chi^2 = 1$

- Cross check with pseudo data MC replicas

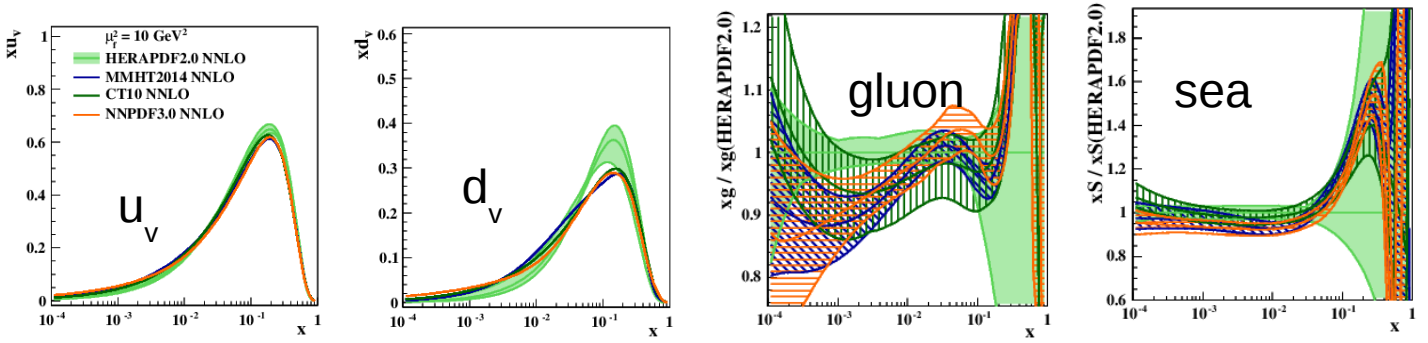
Model uncertainty

Q^2_{min}, f_s, M_c, M_b

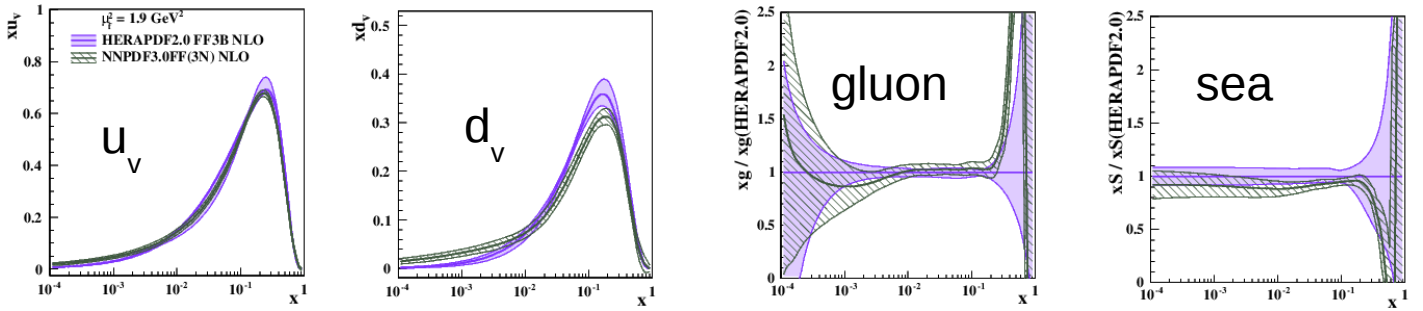
Parametrisation uncertainty

Variation of starting scale
Form of parametrisation (E and D params.)

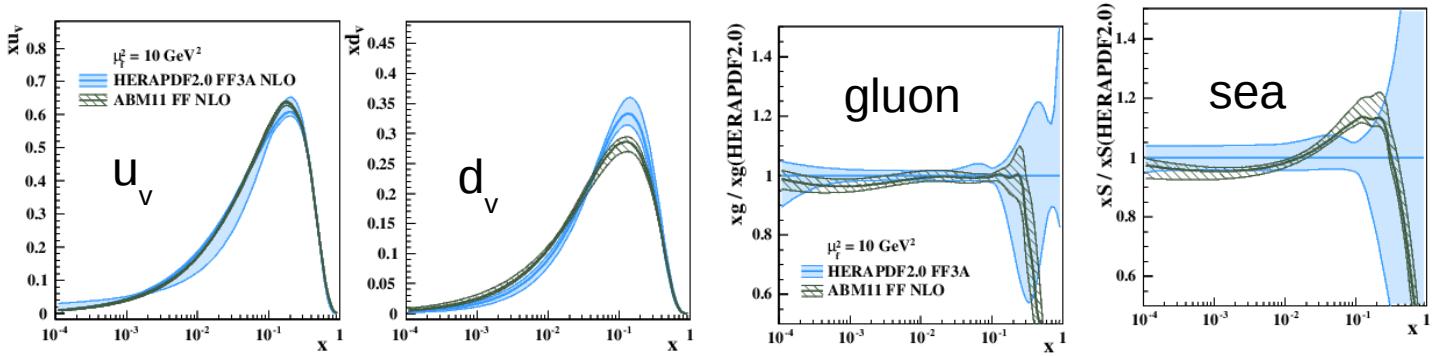
HERAPDF2.0 : Comparison to Modern PDF Fits



VFNS
MMHT2014
CT10
NNPDF3.0



FFNS
NNPDF3.0FF(3N)



FFNS
ABM11 FF

Conclusions

The H1 and ZEUS collaborations measured inclusive $e^{\pm}p$ scattering cross sections at HERA from 1994 to 2007, collecting a total integrated luminosity of about 1 fb^{-1}

The data were combined to create one consistent set of NC and CC cross section measurements for unpolarised scattering, spanning six orders of magnitude in both x and Q^2

The structure functions F_2, xF_3 and F_L are measured

The inclusive cross sections were used as input to a QCD analysis with the DGLAP formalism. The resulting parton distribution functions are denoted HERAPDF2.0 and are available at LO, NLO and NNLO