Precision QCD measurements at HERA

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on behalf of the H1 and ZEUS Collaborations

Covered topics:

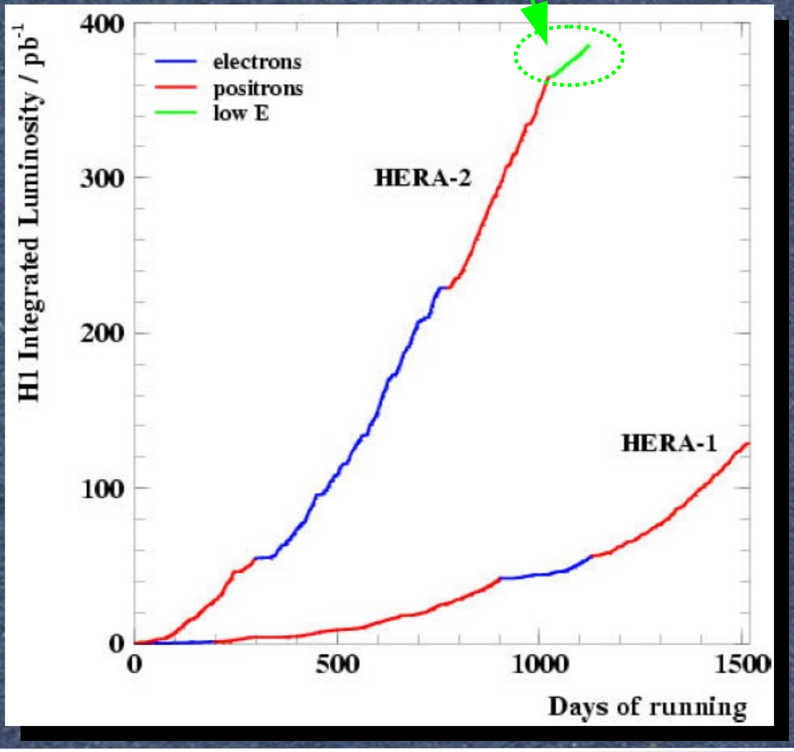
- NC *ep* cross sections at high Bjorken *x* — *Phys.Rev.D89(2014)072007*
- NC *ep* cross sections at large *y* — *DESY-14-053 [arXiv:1404.6376]*
- NC *ep* cross sections at high Q^2 and $\sqrt{s}$ = 225 and 252 GeV and extraction of F_L — *E.P.J.C 74(2014)2814*
- Combination of inclusive *ep* cross sections — *H1prelim-14-041, ZEUS-prel-14-005*
- QCD analysis of combined *ep* cross sections — *H1prelim-14-042, ZEUS-prel-14-007*
- Multijets at high Q^2 and determination of α_s — *DESY 14-089*

QCD@Work, Giovinazzo, 17.06.2014

Introduction

HERA, worlds only *ep* collider, located at DESY, Hamburg

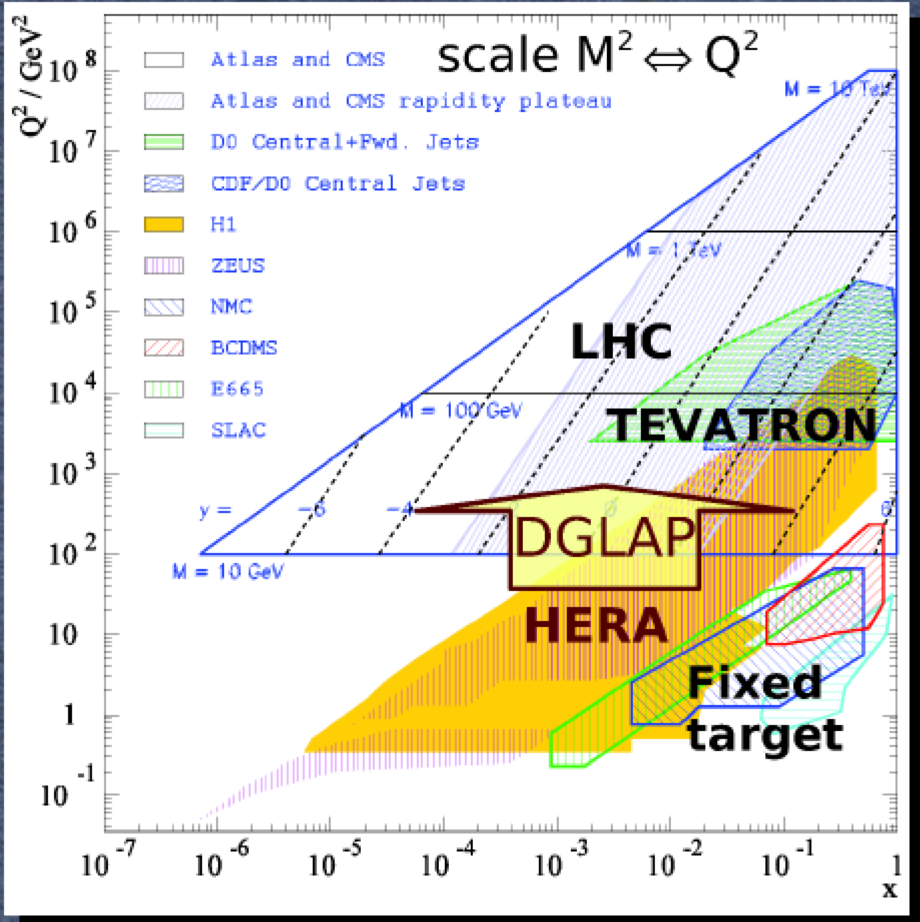
- HERA I: 1992 – 2000
- HERA II: 2003 – 2007
  - Low proton energy runs in the end of HERA operation



Two collider experiments H1 and ZEUS
- Collected ~$0.5 fb^{-1}$ of data per experiment

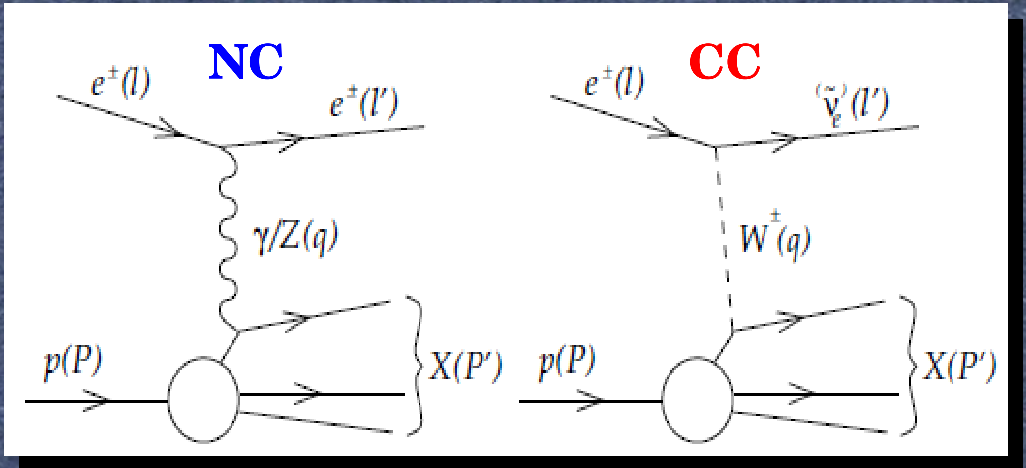
Inclusive deep inelastic *ep* scattering (DIS)

- HERA data covers a wide range in *x*.



- DGLAP allows to evaluate PDFs from HERA to the LHC region.

- Neutral and charged current processes



Virtuality of exchanged boson:

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

Bjorken scaling variable:

$x = Q^2 / (2P \cdot q)$

Inelasticity:

$y = (P \cdot q)/(P \cdot l)$

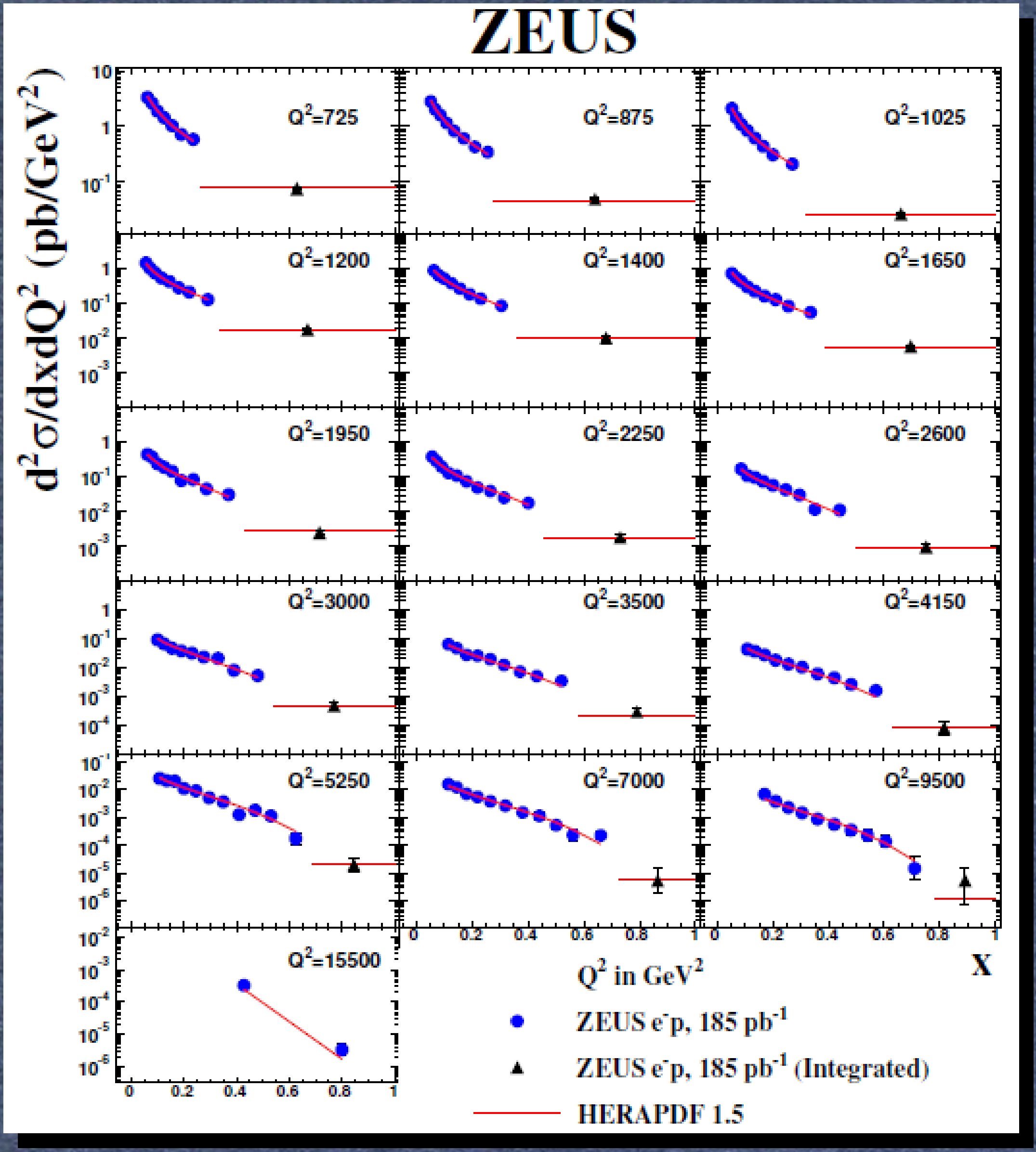
Centre of mass energy squared:

$s = (l + P)^2 = Q^2 / (x \cdot y)$

- NC and CC processes provide a unique opportunity to study proton's structure

NC *ep* cross section measurement at high *x*

Phys.Rev.D89(2014)072007



- High x available from fixed target experiments only is at low Q^2.
- Measuring high x high Q^2 data allows to have additional constrains on PDFs in that region.
- NC ep DIS cross sections at $Q^2 > 725$ GeV^2 up to $x \cong 1$ measured by ZEUS detector.
- The measurement shows a good agreement with the Standard Model predictions.

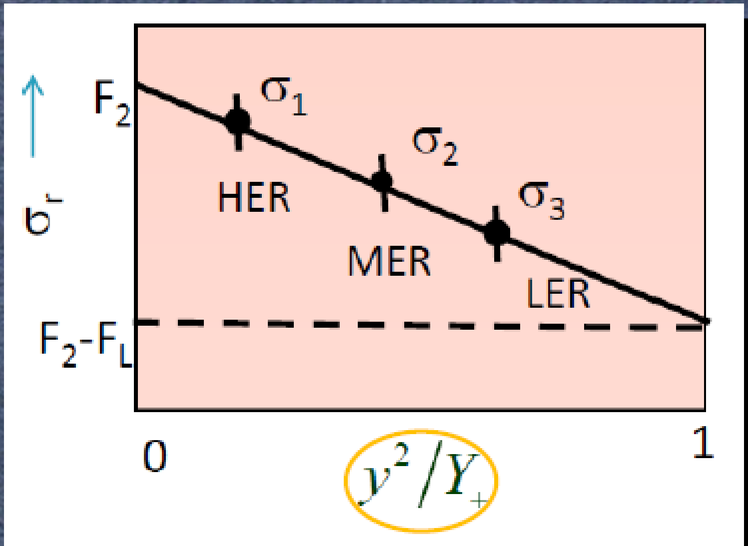
NC cross section and F_L structure function

E.P.J.C 74(2014)2814, DESY-14-053 [arXiv:1404.6376]

At moderate values of Q^2:

$$\tilde{\sigma}_{NC}(x,Q^2,y) = \frac{d^2\sigma_{NC}^{ep}}{dxdQ^2} \cdot \frac{xQ^4}{2\pi\alpha Y_+} = F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2)$$

where $Y_+ = 1 + (1-y)^2$



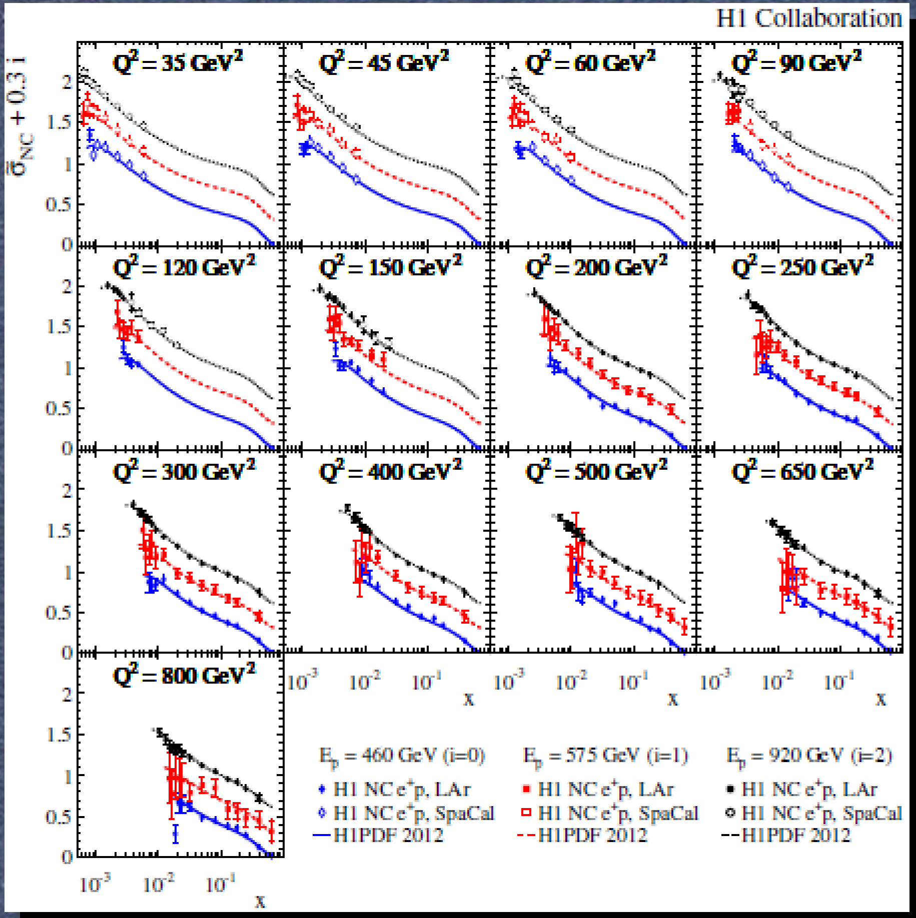
- Bulk of HERA data: √s = 318 GeV (HER)
- By the end of HERA run: √s = 225 GeV (LER) and √s = 251 GeV (MER) data
- This allows to measure NC cross sections at fixed x and Q^2 for different values of y → disentangle F_L and F_2 structure functions

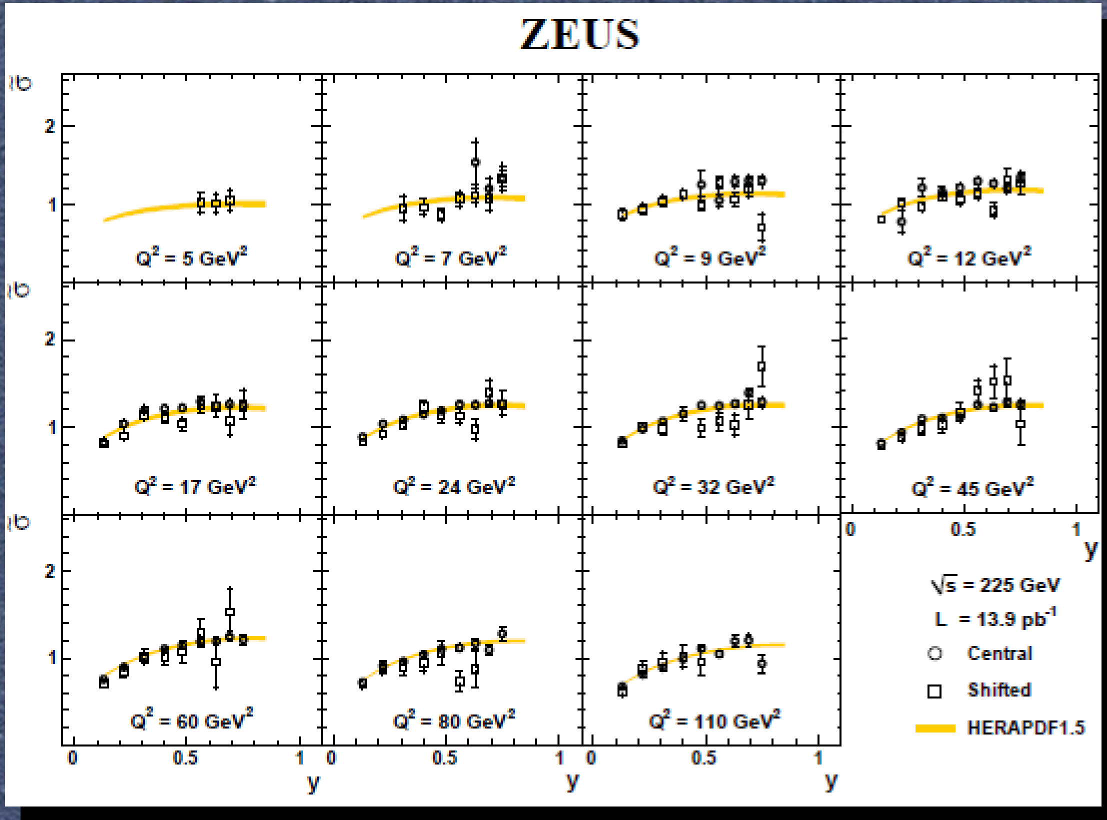
- **F_L is a QCD effect, direct measurement of which allows to test pQCD**
- **F_L is directly sensitive to the gluon**

NC *ep* cross section at $\sqrt{s}$ = *225, 251* and *318* GeV

E.P.J.C 74(2014)2814, DESY-14-053 [arXiv:1404.6376]

NC cross sections measured by the H1 and by ZEUS at different center of mass energies.





Extraction of longitudinal structure function F_L

E.P.J.C 74(2014)2814, DESY-14-053 [arXiv:1404.6376]

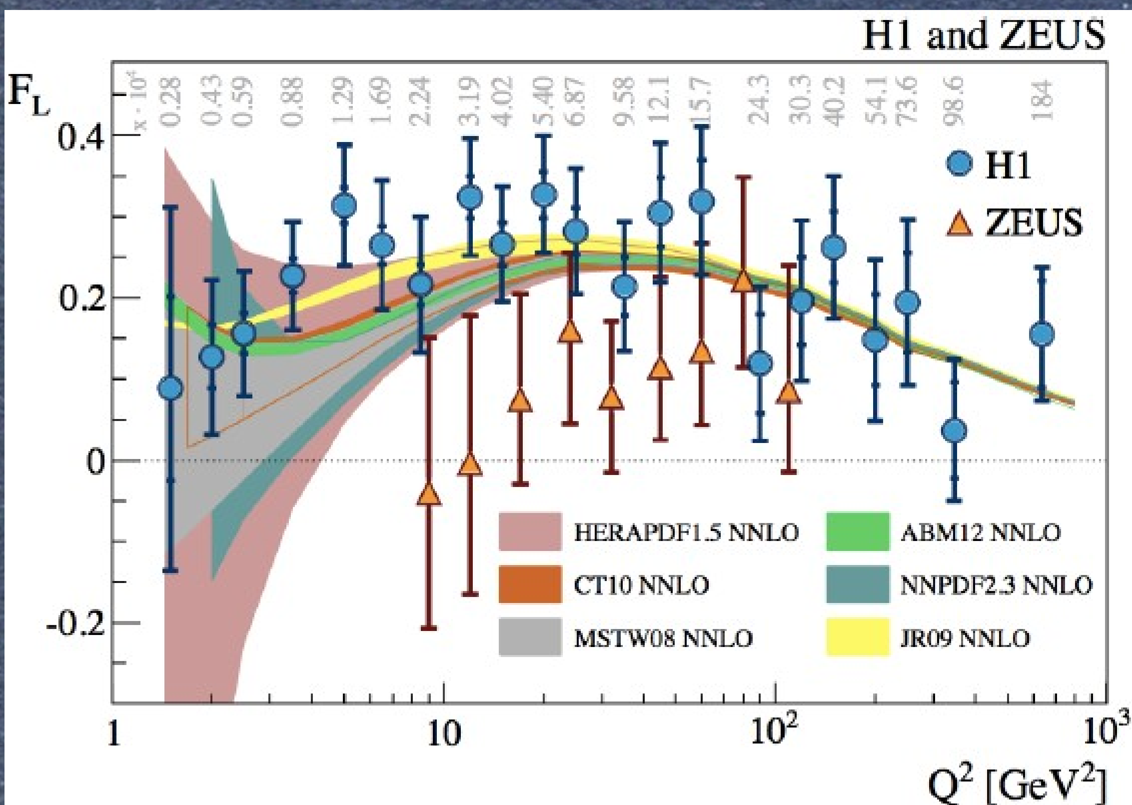
- F_2 and F_L are simultaneously determined by the H1 from a χ^2 fit, taking correlated systematics into account using HER, MER and LER cross sections.

$$\chi^2(F_{L,i}, F_{2,i}, b_j) = \sum_i \frac{\left[(F_{2,i} - f(y_i)F_{L,i}) - \sum_j \Gamma_{i,j} b_j - \mu_i\right]^2}{\Delta_i^2} + \sum_j b_j^2$$

$$\Delta_i = \sqrt{(\Delta_{i,stat}^2 + \Delta_{i,syst}^2)}$$

The formula is labelled as follows:

- sum over corr. syst.
- syst. err. matrix
- nuisance param.
- sum over data points
- prediction and free parameters F_2 and F_L
- measured cross section



- Similar technique is used by ZEUS.
- A good agreement between NNLO predictions and the measurements
- Overall consistency between the H1 and ZEUS about 1 – 2σ.

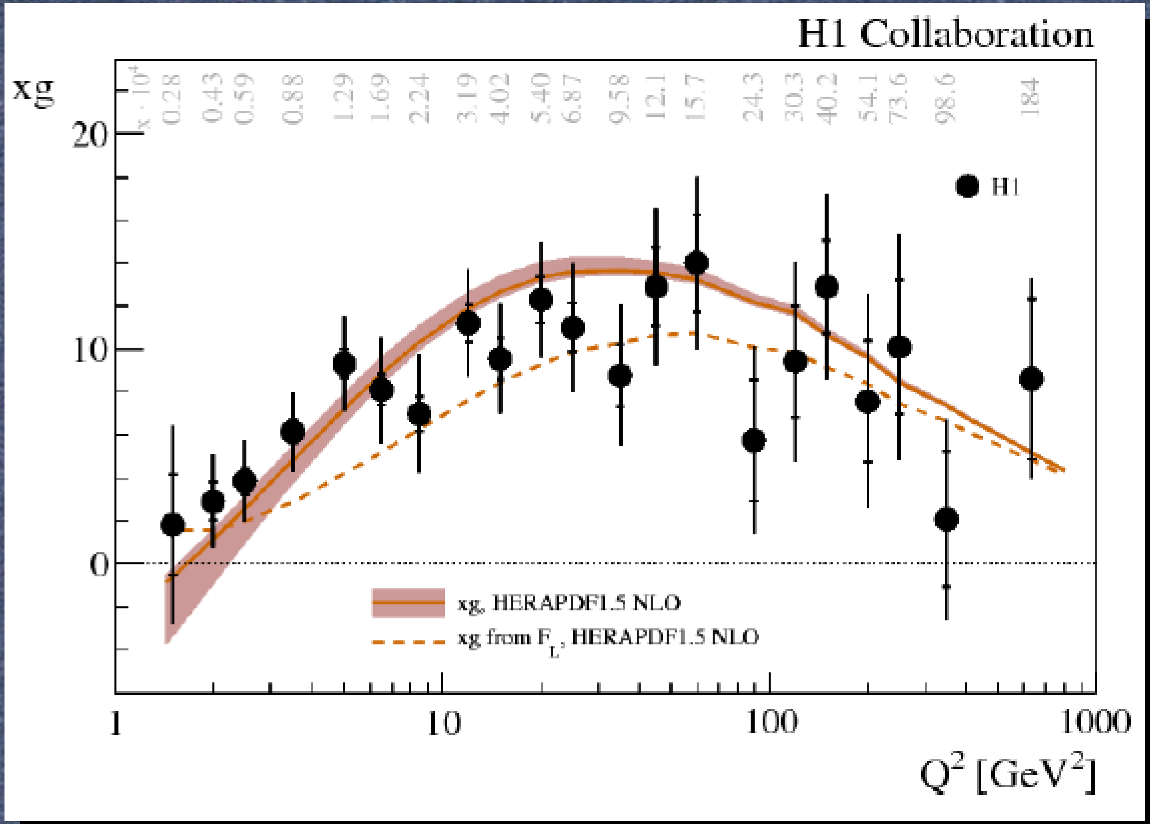
NOTE: Sizable bin-to-bin correlations!

Extraction of longitudinal structure function F_L

E.P.J.C 74(2014)2814, DESY-14-053

F_L allows to directly measure gluon density:

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



- Gluon density extracted from F_L (solid points) is compared to the gluon density from set of PDFs HERAPDF1.5 (shadowed area) as well as to the result of applying the equation above to the F_L prediction based on HERAPDF1.5 (dashed line).

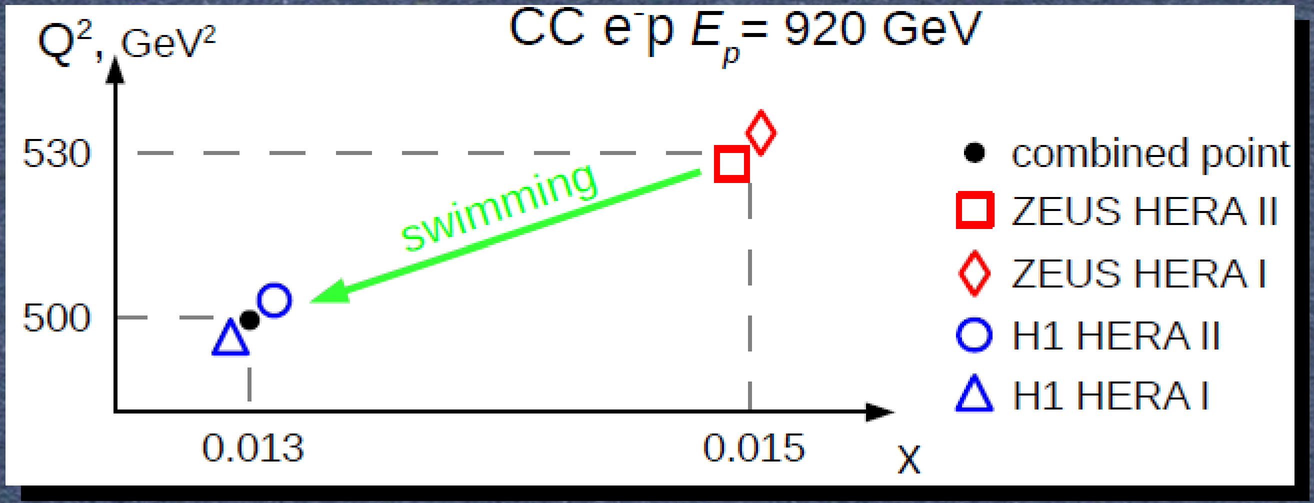
- Gluon density extracted directly from F_L reasonably well agrees with the gluon density from HERAPDF1.5.

Inclusive DIS combination

H1prelim-14-041, ZEUS-prel-14-005

- HERA II data provides a great statistical improvement compare to the HERA I data.
- In total 41 final data sets of HERA (about 3000 data points!) inclusive measurements.

NOTE:
the next bin in Q^2 is at *800* GeV²
the correction is very small!

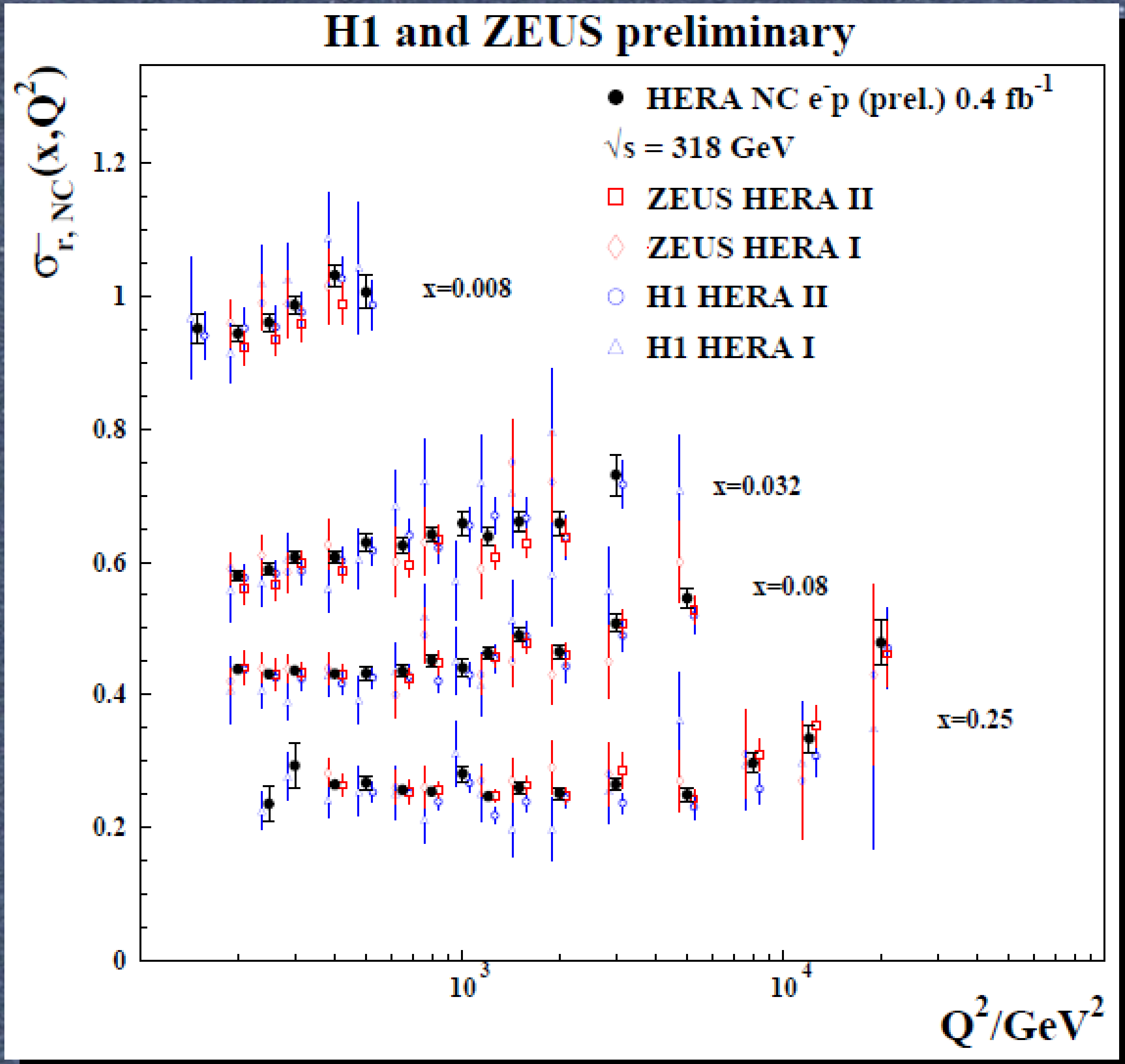


Combination is performed with HERAverager tools based on χ^2 minimisation method and is done in two steps:

1) Swim all data points to a common $x - Q^2$ grid
2) Average cross section values

Inclusive DIS combination

H1prelim-14-041, ZEUS-prel-14-005



- Data is consistent between HERA I and HERA II as well as between two experiments
- Large uncertainty reduction, especially in e^-p due to 10x increase in luminosity.
- Larger HERA II luminosity yields in significant improvement in precision at high x and Q^2.

QCD analysis of combined DIS cross sections

H1prelim-14-042, ZEUS-prel-14-007

- Final HERA I + II combined inclusive DIS data is as an input to a QCD analysis.

QCD fit is performed using HERAFitter open source QCD fit framework, available at *www.herafitter.org*

- The PDFs are parametrised at the starting scale $Q^2 = 1.9$ GeV^2 as follows:

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

$$xu_v(x) = A_{u_v} \cdot x^{B_{u_v}} \cdot (1-x)^{C_{u_v}} \cdot (1 + D_{u_v} x + E_{u_v} x^2)$$

$$xd_v(x) = A_{d_v} \cdot x^{B_{d_v}} \cdot (1-x)^{C_{d_v}}$$

$$x\bar{U}(x) = A_{\bar{U}} \cdot x^{B_{\bar{U}}} \cdot (1-x)^{C_{\bar{U}}} \cdot (1 + D_{\bar{U}} x)$$

$$x\bar{D}(x) = A_{\bar{D}} \cdot x^{B_{\bar{D}}} \cdot (1-x)^{C_{\bar{D}}}$$

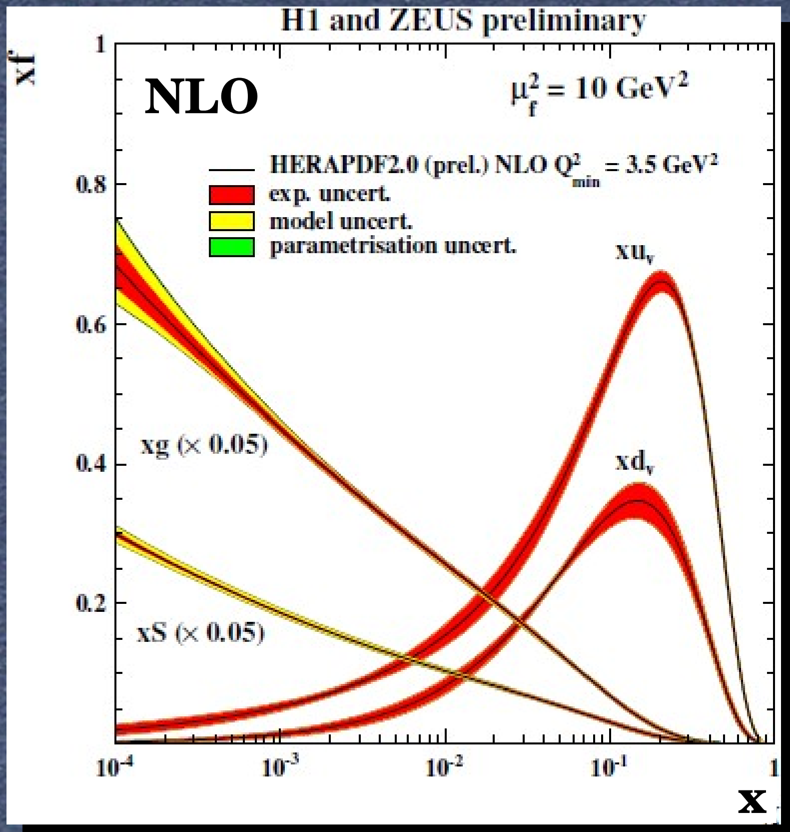
* $x\bar{U} = x\bar{u}$, $x\bar{D} = x\bar{d} + x\bar{s}$,
  $xs = x\bar{s}$, $x\bar{s} = r_s x\bar{d}$
  normalisation parameters: A_{u_v}, A_{d_v}, A_g
* Condition that $x\bar{u} \to x\bar{d}$ as $x \to 0$
  constrains $B_{\bar{U}} = B_{\bar{D}}$ and $A_{\bar{U}} = A_{\bar{D}} / (1 + r_s)$
* *15* free parameters

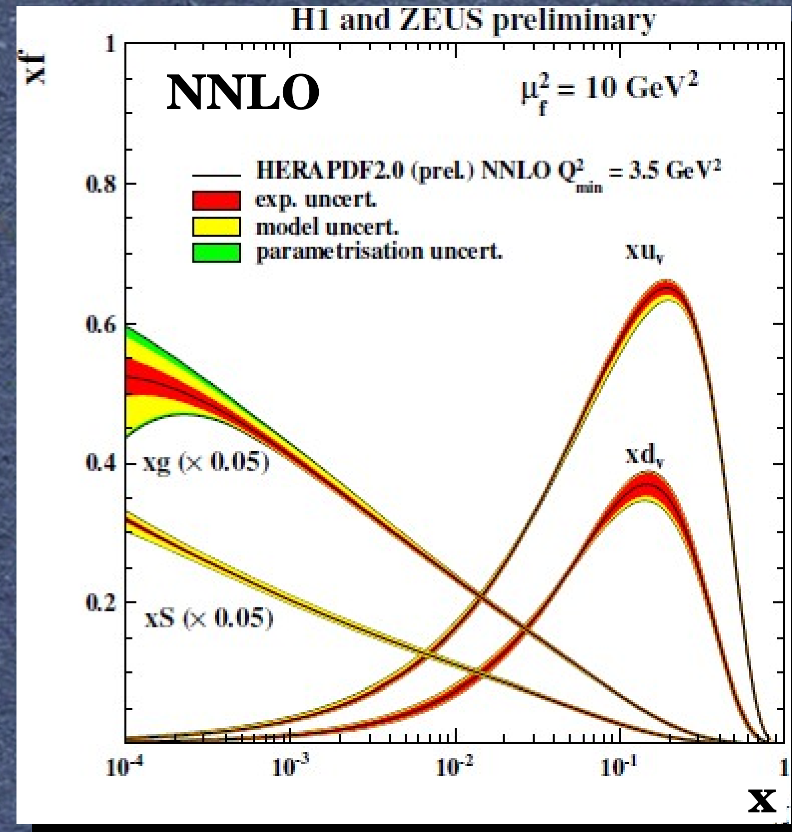
- PDFs are then evolved via DGLAP evolution equations to NLO and NNLO using QCDNUM package.
- Heavy quarks are treated using Thorne-Roberts General Mass Variable Flavor Number Scheme

HERAPDF 2.0

H1prelim-14-042, ZEUS-prel-14-007

- PDFs are determined by minimizing χ^2 function with the respect to PDF parameters.

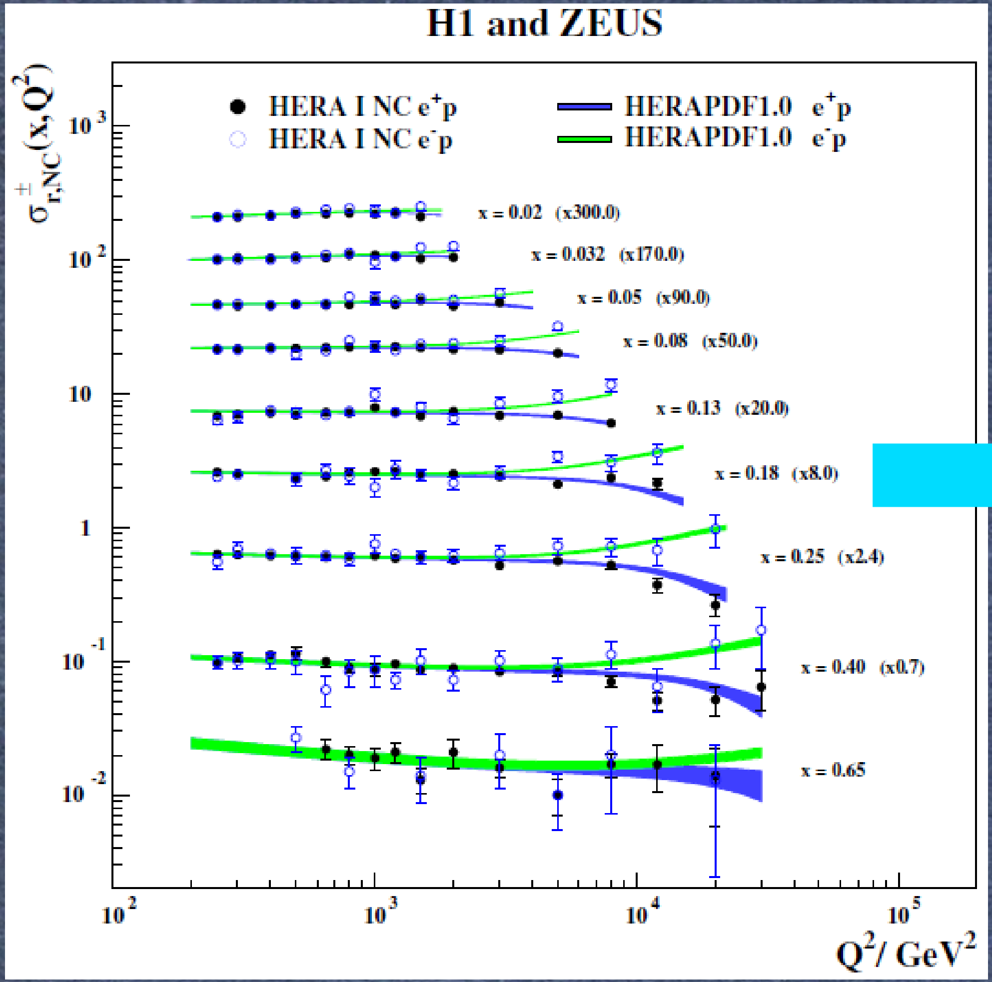


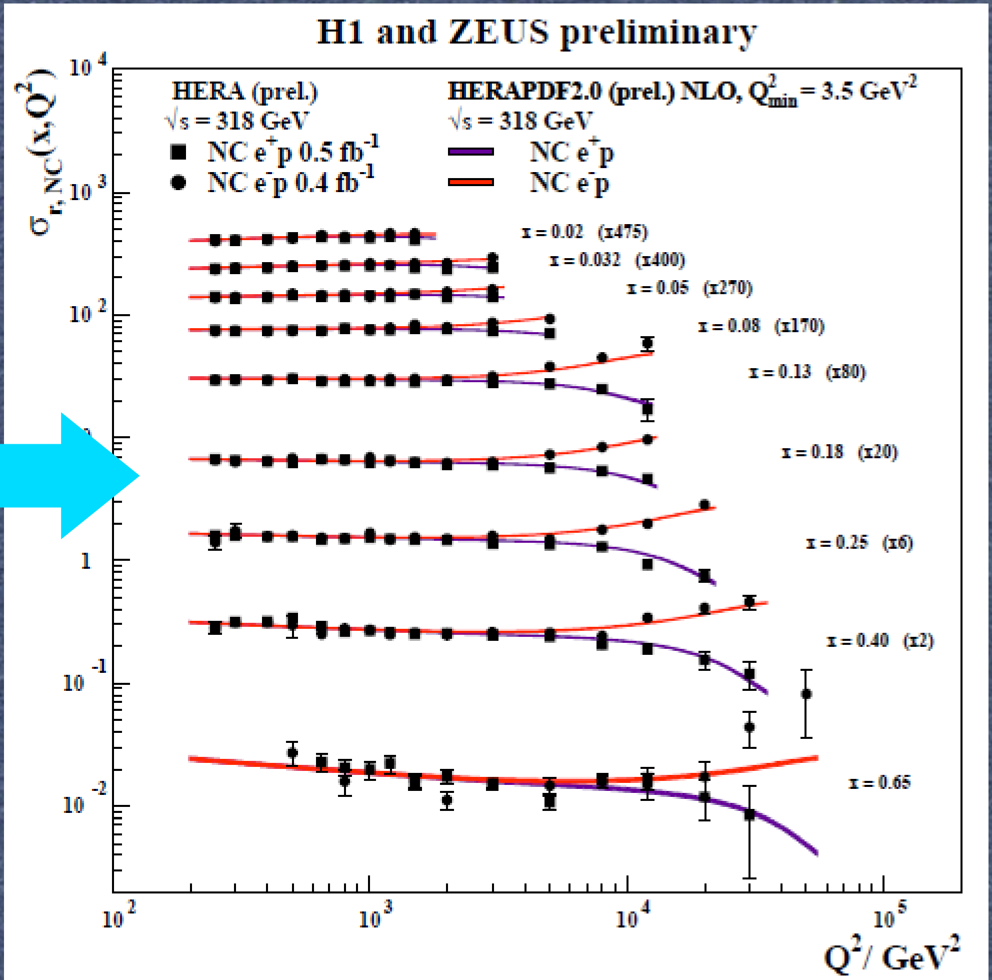


- Red → experimental uncertainty, estimated using Hessian method.
- Yellow → model uncertainty, from variation of quark masses, α_s etc.
- Green → an envelope from PDF fits using variants of parametrisation form (extra D or E parameters in polynomial) as well as starting scale variations.

HERAPDF 2.0

H1prelim-14-042, ZEUS-prel-14-007

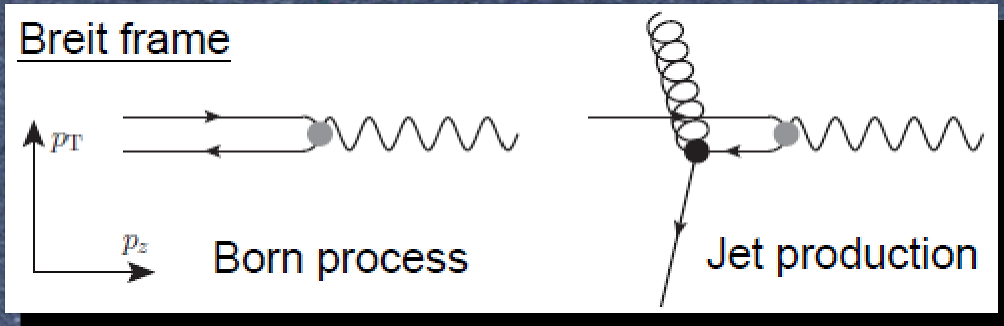




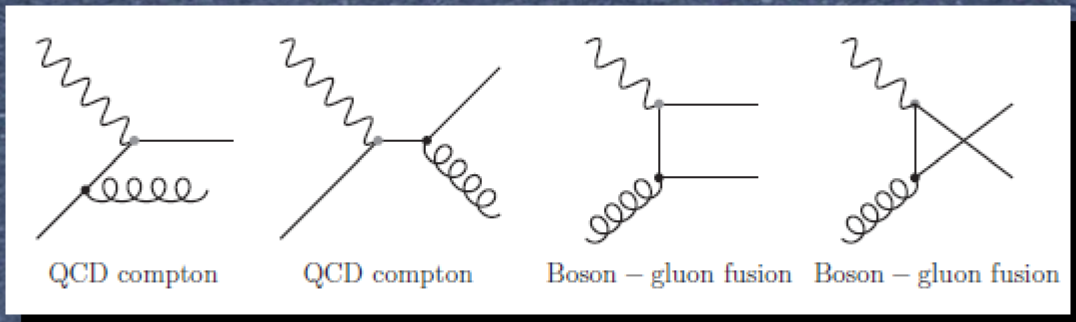
- Combined HERA I inclusive NC cross sections compared to predictions from HERAPDF1.0
- Great precision achieved both in data and in HERAPDF2.0, by combining HERA I and HERA II measurements.

Multijet production in DIS at high Q^2

- Jet measurements are performed in 'Breit frame', where the virtual boson collides head on with a parton from the proton



- Jet production in LO pQCD

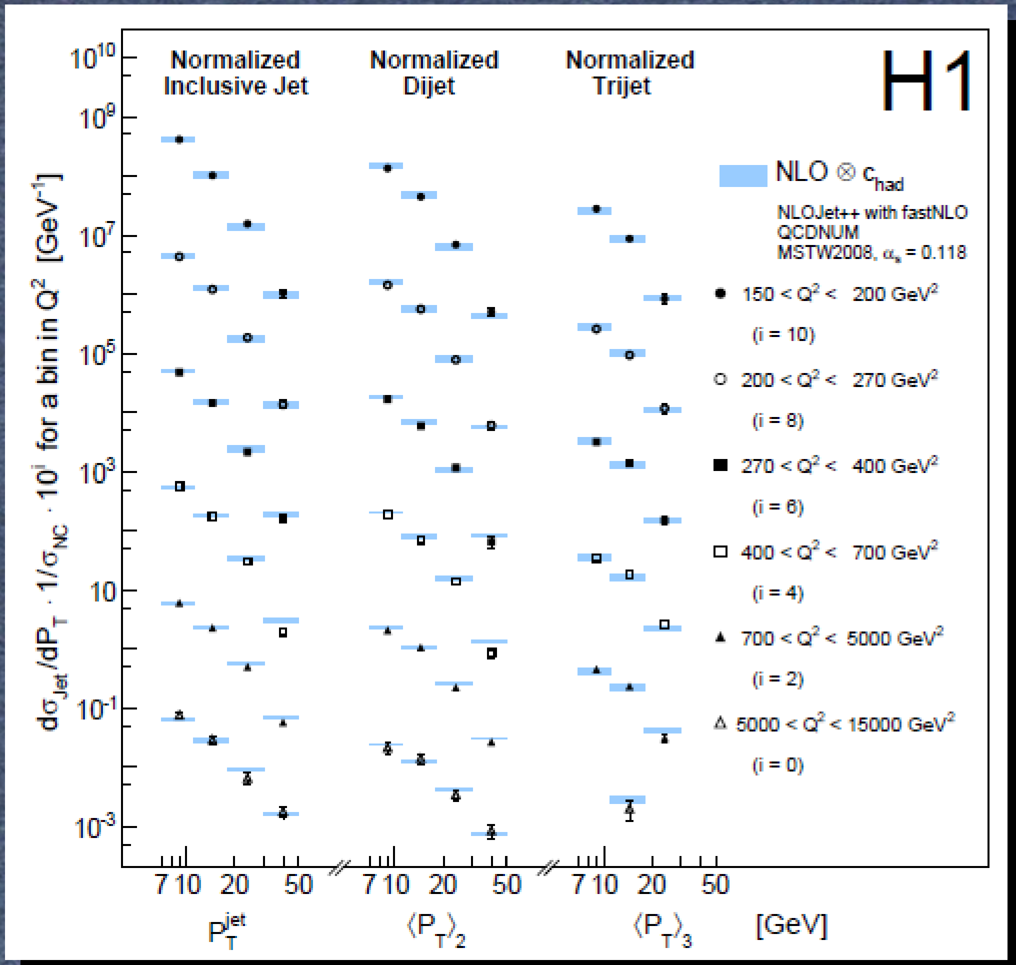


- Jet production is an important process for studying strong interactions and is directly sensitive to α_s

Multijet production in DIS at high Q^2

DESY 14-089

- Double-differential inclusive jet, dijet and trijet cross sections are measured by the H1 experiment using regularized unfolding.

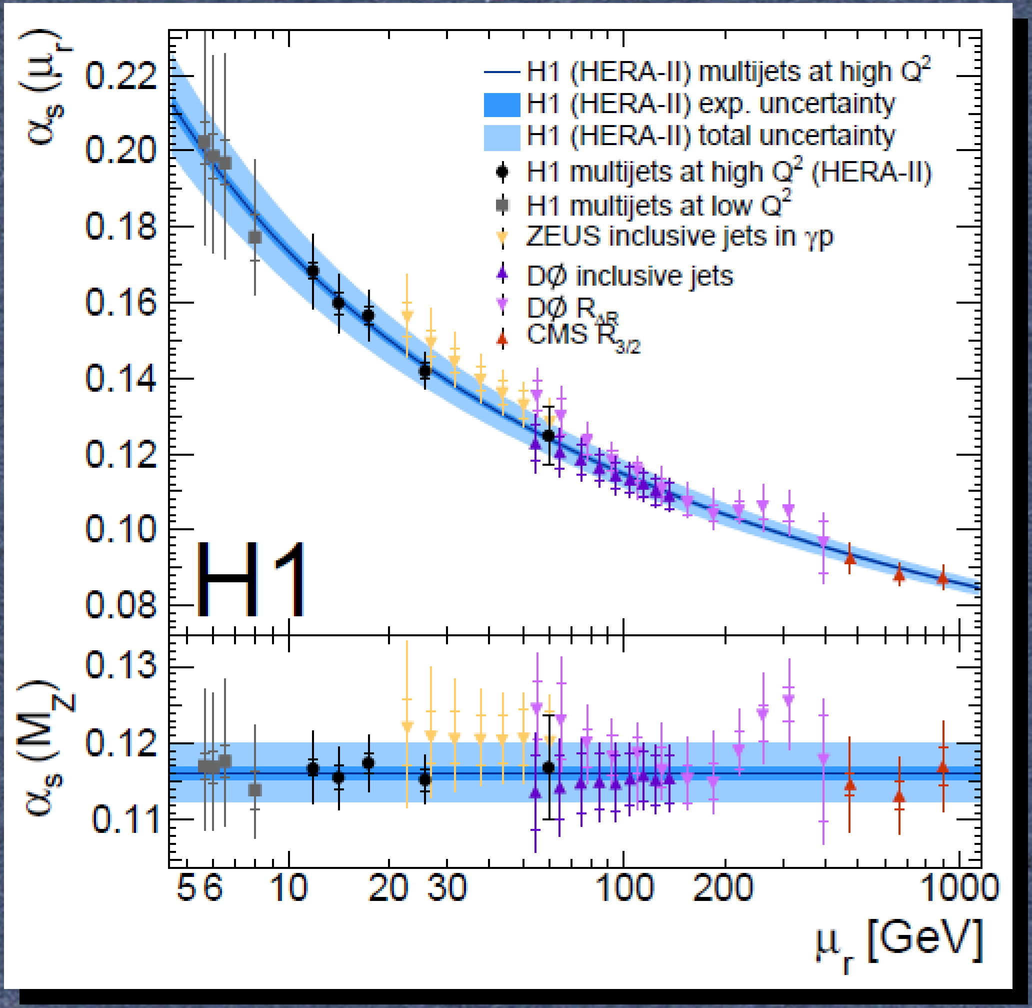


- Measured absolute cross sections is then normalised to the NC DIS cross section to benefit from cancellation of systematic uncertainties correlated between the measurements.
- Theoretical predictions are at NLO and are based on NLOJet++, fastNLO, QCDNUM and MSTW2008 set of PDFs, $\alpha_s = 0.118$.
- Blue band corresponds to NLO uncertainty, obtained by varying renormalisation scale $\mu^2=(Q^2+P_T^2)/2$.

Multijet production at high Q2

DESY 14-089

- α_s is extracted by fitting each jet cross section separately and also all three simultaneously taking into account the covariance matrix from unfolding.



- The running of the strong coupling α_s as a function of the scale μ_r (top) as well as the corresponding values of α_s (M_Z) (bottom).

- Shown also are α_s values measured by ZEUS, D∅ and CMS experiments.

$\alpha_s = 0.1165 \pm 0.0008_{exp} \pm 0.0038_{theo}$

Theoretical uncertainty is about five times larger than experimental uncertainty!

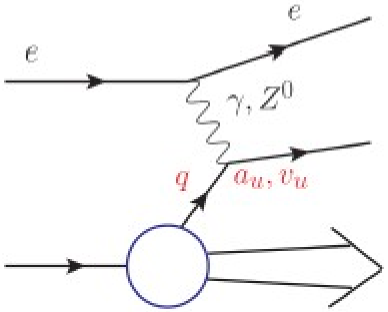
Summary

- Latest measurements of DIS cross section at very high x by ZEUS are expected to provide constrains on the PDFs at high x region, where the contribution of valence quarks is important.
- Measurements in the high y region by both H1 and ZEUS allow to decouple F_2 and F_L structure functions thus providing direct sensitivity to the gluon.
- The total luminosity of about *1* fb^{-1} collected by the experiments provides cross sections of very high precision, which are used for a clean determination of the proton's PDFs based solely on *ep* collider data.
- New preliminary combined HERA I + II measurements improve precision of PDFs.
- The measurement of jet production in DIS by H1 allows for testing QCD predictions and for a precise determination of the strong coupling constant α_s.

Backup

Inclusive deep inelastic *ep* scattering (DIS)

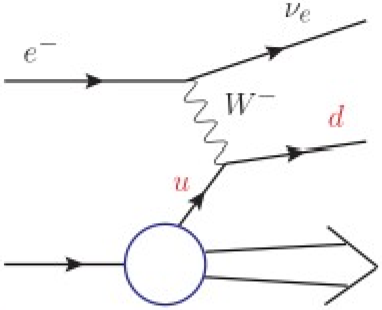
Neutral Current :

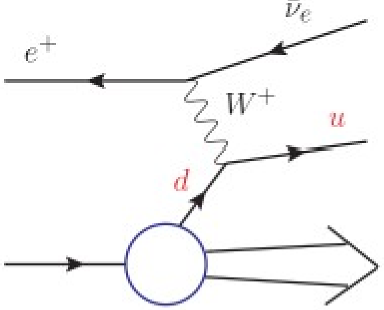


$$\frac{d^2\sigma_{NC}^{e\mp p}}{dxdQ^2}=\frac{2\pi\alpha^2\cdot Y_+}{xQ^4}\cdot\left(F_2(x,Q^2)\pm\frac{Y_-}{Y_+}\cdot x\cdot F_3(x,Q^2)-\frac{y^2}{Y_+}\cdot F_L(x,Q^2)\right)$$

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

Charged Current :





$$\frac{d^2\sigma_{CC}^{e\mp p}}{dxdQ^2}=\frac{G_F^2}{4\pi x}\cdot\kappa^2\cdot\left(Y_+\cdot W_2^\mp\pm Y_-\cdot x\cdot W_3^\mp-y^2\cdot W_L^\mp\right)$$

$$\kappa=\frac{M_W^2}{M_W^2+Q^2}$$

HERAPDF 2.0

- Comparison of HERAPDF 2.0 to HERAPDF 1.0 at NLO (left) nad NNLO (right)