Recent results from HERA on the proton structure

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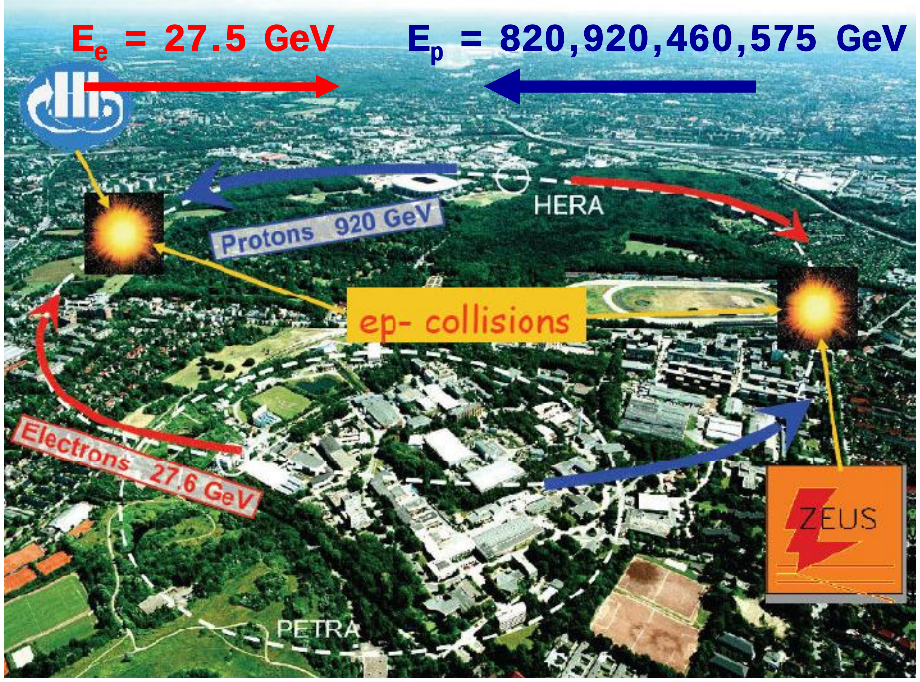
On behalf of the H1 and ZEUS Collaborations

Outline:

- Introduction – HERA and DIS physics
- New preliminary result on PDFs from HERA
- New result on neutral current cross section at high Bjorken x
- New result on longitudinal structure function at high Q^2
- Summary

HERA and luminosity



HERA (DESY, Hamburg): 1992 - 2007

- Total lumi H1, ZEUS: 0.5 fb^{-1} each

  HERA-I 1992-2000 ~120 pb^{-1}

  HERA-II 2003-2007 ~380 pb^{-1}

$E_{e+/e-}$ = 27.6 GeV

HERA-I (E_p = 820, 920 GeV) upgraded to HERA-II (E_p = 920 GeV)

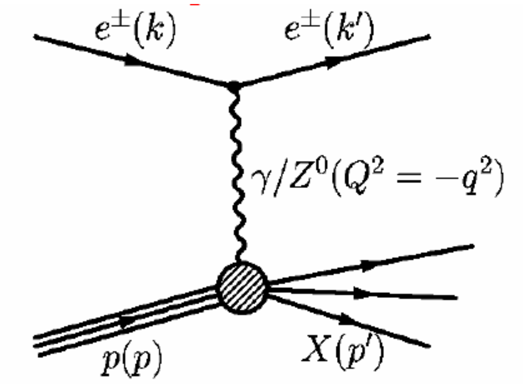
Since April 2007 until the end of June

- Low energy run – LER - (E_p = 460 GeV)
- Medium energy run – MER - (E_p = 575 GeV)

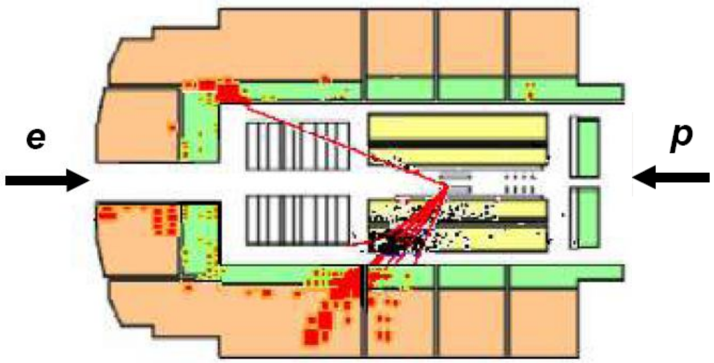
} Measurement of F_L

Inclusive Deep Inelastic Scattering (DIS)

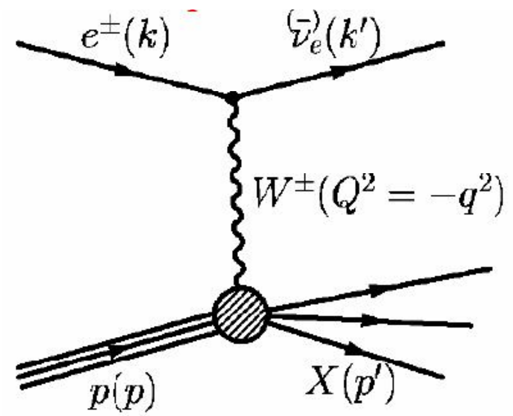
Neutral Current (NC)



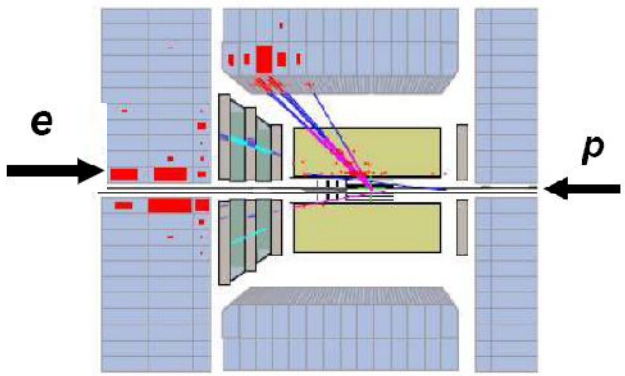
H1 NC event display



Charged Current (CC)



ZEUS CC event display



Virtuality of exchanged boson:

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

Fraction of proton momentum carried by struck quark

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

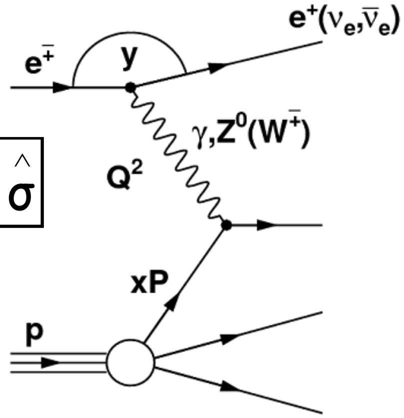
Fraction of energy transferred from incoming lepton at proton rest frame

$$y = \frac{p\cdot q}{p\cdot k}$$

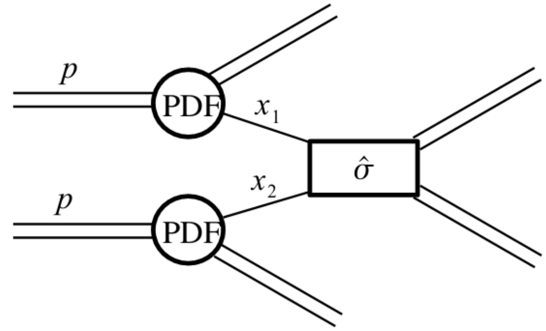
HERA Parton Denisty Functions (PDFs) and the LHC

HERA:

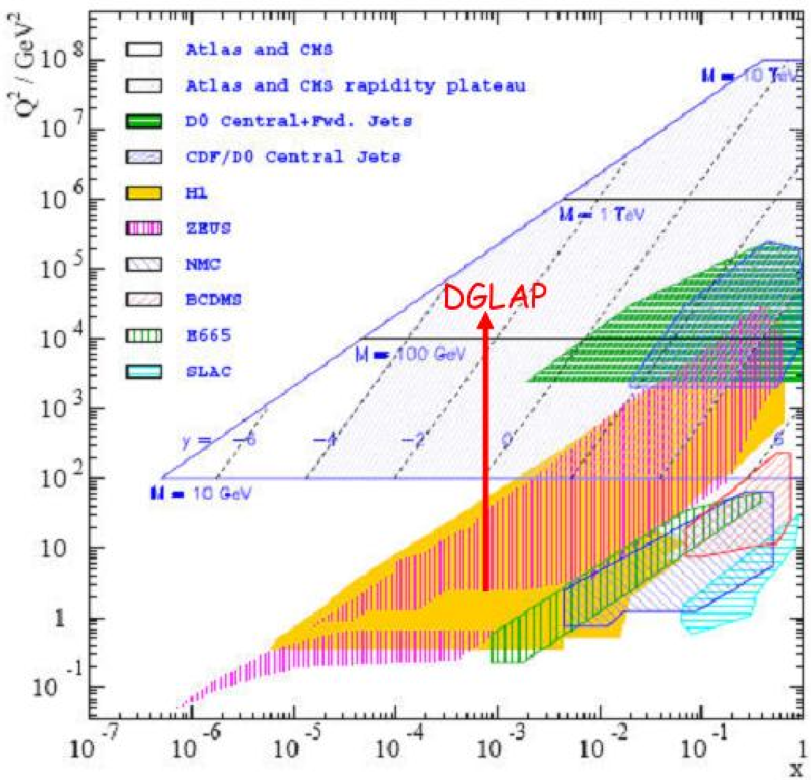
$$\sigma \propto \mathrm{PDF}(x) \times \hat{\sigma}$$



LHC:



$$\sigma \propto \mathrm{PDF}(x_1) \times \mathrm{PDF}(x_2) \times \hat{\sigma}$$



- ❑ Proton structure described by precise PDFs needed for making accurate predictions for any process involving protons

- ❑ **DGLAP QCD** evolution provides Q^2 dependence of the PDFs, x dependence must come from data. HERA covers the most important region for the LHC

NC and CC cross sections

Neutral current cross section

$\tilde{\sigma}_{NC}(x, Q^2)$ - NC reduced cross-section

$$\frac{d^2\sigma_{NC}(e^\pm p)}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4} Y_+\left[F_2 - \frac{y^2}{Y_+}F_L \mp \frac{Y_-}{Y_+}xF_3\right] \qquad Y_\pm = 1 \pm (1-y)^2$$

Contribution from valence and see quarks

Directly related to gluon in pQCD $F_L \sim \alpha_s \cdot xg(x,Q^2)$ (**sizable only at high y**)

Contribution from valence quarks at high Q^2

Charged current cross section

$$\frac{d^2\sigma_{cc}^{e^\pm p}}{dxdQ^2} = \frac{G_F^2 M_W^4}{2\pi x(Q^2 + M_W^2)^2}\sigma_{cc}^\pm$$

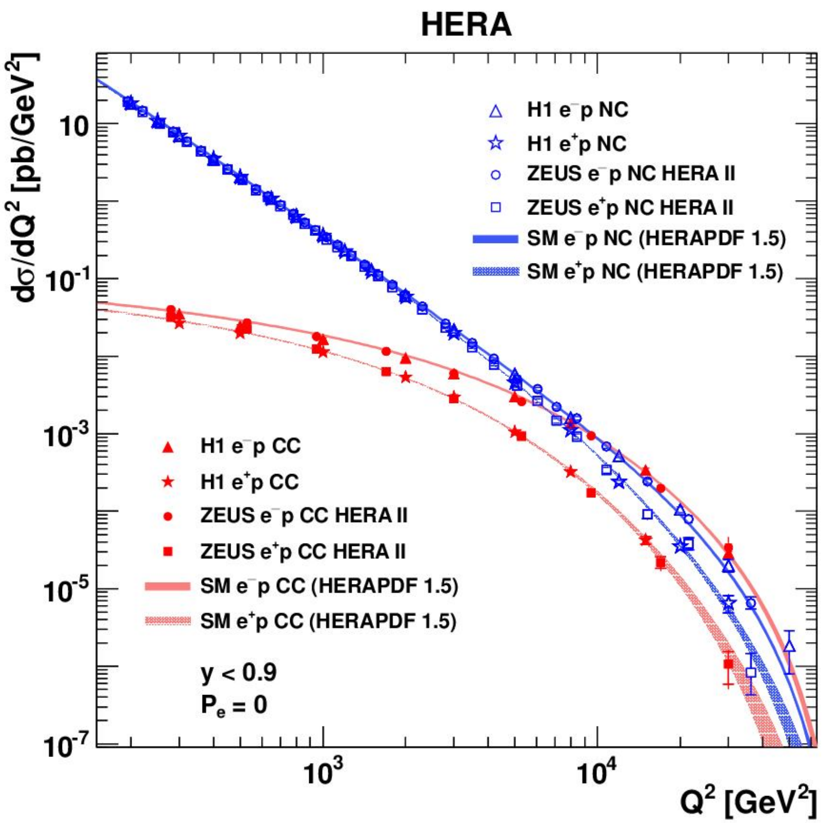
$$\sigma_{cc}^{e^+p} \sim (x\bar{u} + x\bar{c}) + (1-y)^2(xd + xs)$$

$$\sigma_{cc}^{e^-p} \sim (xu + xc) + (1-y)^2(x\bar{d} + x\bar{s})$$

Sensitivity to the flavor of the valence distributions at high x

- Direct measure of structure functions (various linear combination of PDFs)
- HERA can disentangle proton PDFs with little assumptions

H1 and ZEUS NC and CC cross sections and PDFs



- H1 and ZEUS published high precision measurements of NC and CC cross sect. **Q^2 from 0.045 GeV^2 to 40000 GeV^2** **x from $6 \cdot 10^{-7}$ to 0.65**
- Allow PDFs to be extracted solely from these data
- To get high precision measurements of PDFs H1 and ZEUS results are combined → HERAPDF sets
- The total errors are around 1% for $20 < Q^2 < 100$ GeV^2 and less than 2% for most of the rest of kinematic plane

- **HERAPDF1.0 NLO**: based on published NC+CC HERA-I data - published
- **HERAPDF1.5 NLO**: based on preliminary NC+CC HERA-I+HERA-II data
- **HERAPDF1.5 NNLO**: based on preliminary NC+CC HERA-I+HERA-II data
- All the HERAPDF sets are obtained with uncertainties: exp. + model + theory

New preliminary PDF fit from HERA at LO – motivation

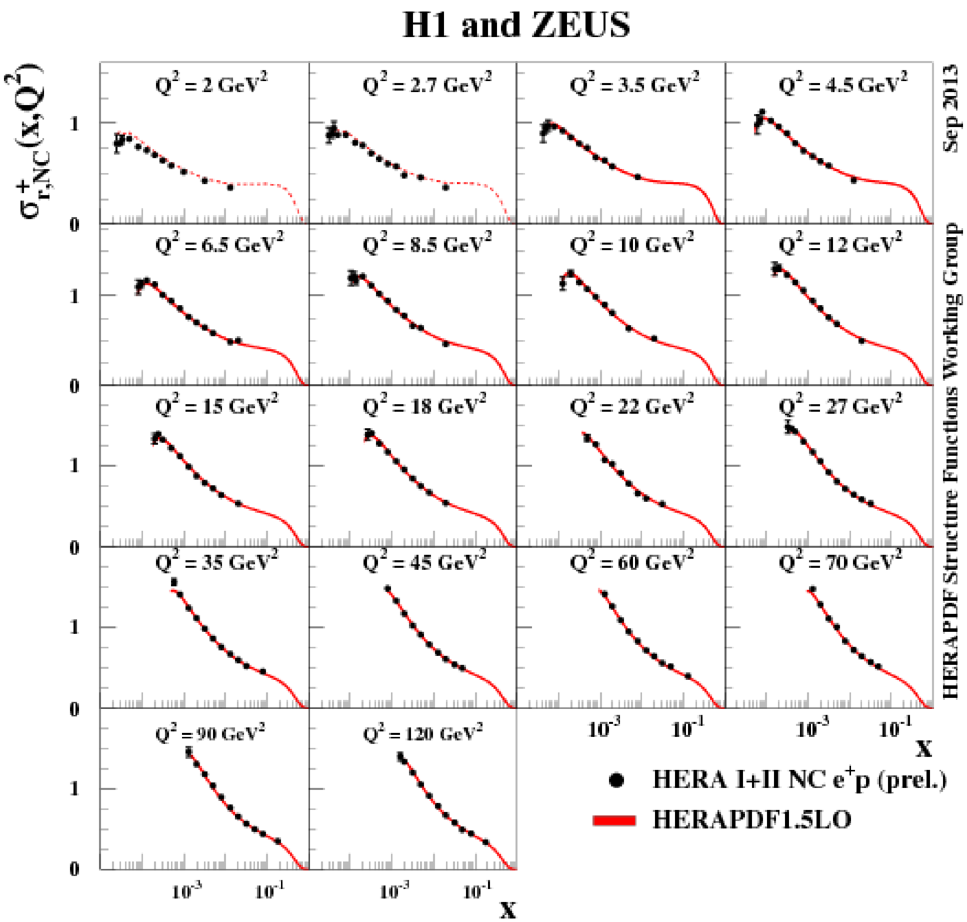
- Parton densities evolved to leading order (LO) in α_s are essential for the proper simulation of parton showers (PS) and underlying event properties in LO+PS MC event generators and also for minimum bias events and the simulation of pile-up events
- The higher energies at the LHC correspond to lower values of x → the HERAPDF sets with its special emphasis on the small-x structure functions important input for the MC generators
- New at HERA: the HERAPDF1.5 LO set based on the same data sets and settings as HERAPDF1.5 NLO PDF set: **H1prelim-13-141, ZEUS-prel-13-003**

➢ The PDFs are evolved using the DGLAP evolution equations at LO

➢ $\alpha_s(M_Z) = 0.13$ - obtained from the best level of agreement between data and the fit

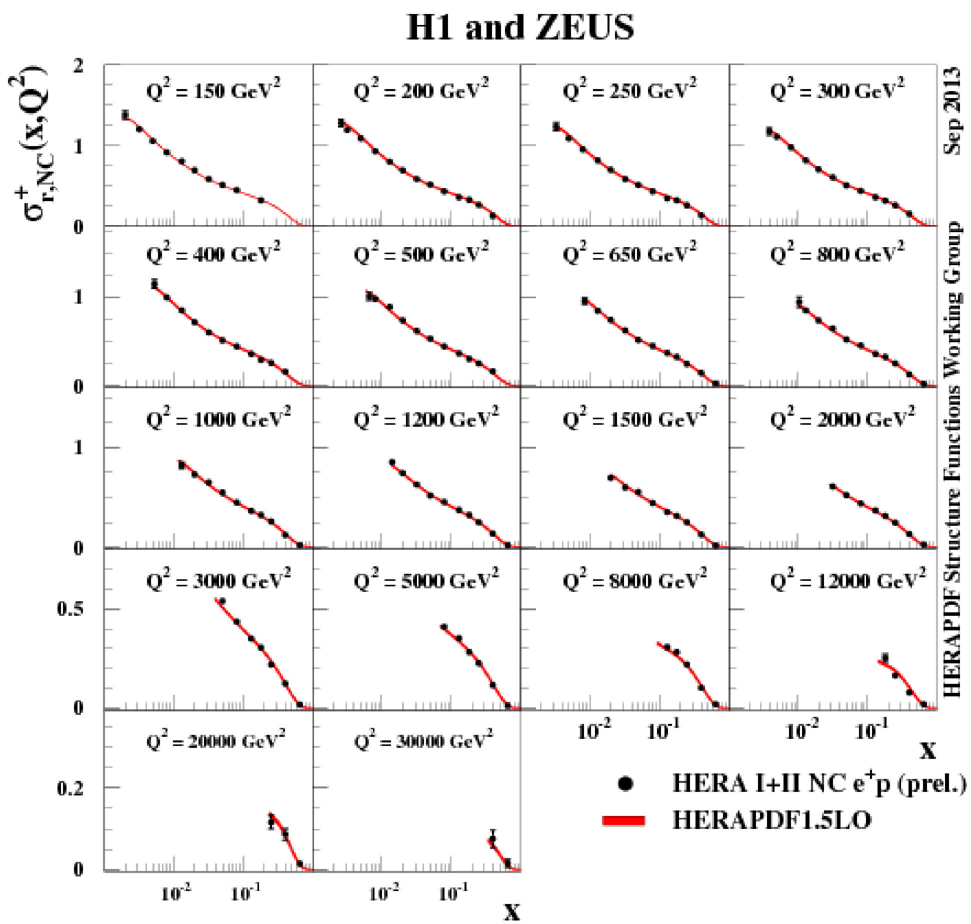
➢ The experimental uncertainties on the PDFs are determined using the $\Delta\chi^2 = 1$ criterion leading to uncertainties with a confidence level of 68%

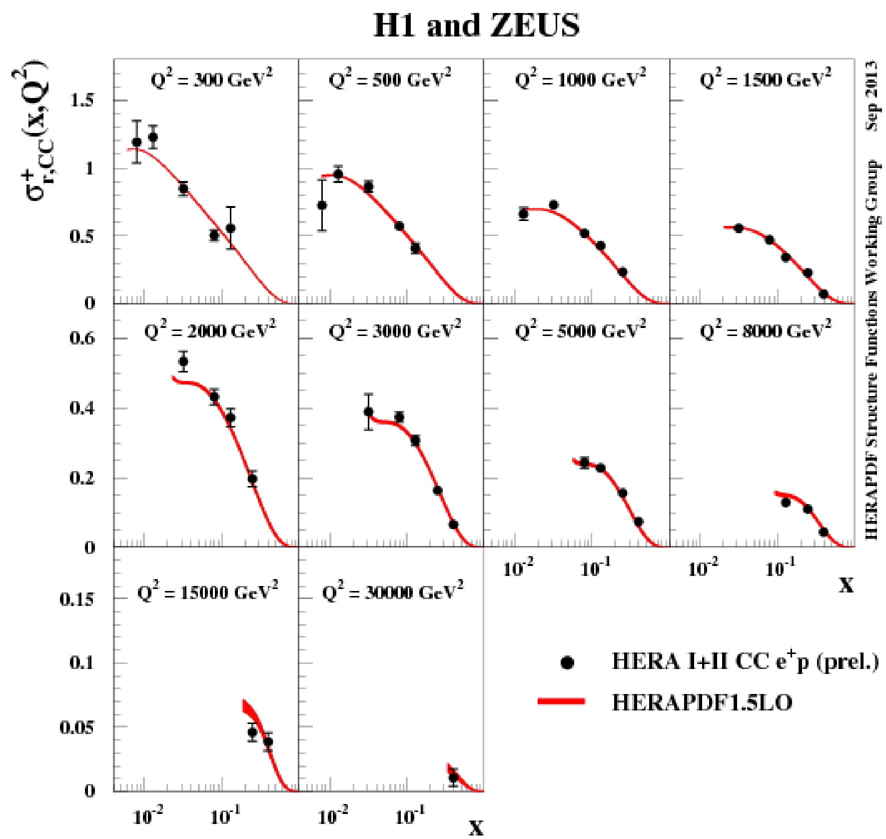
Comparison of low Q^2 NC e^+p data with the HERAPDF1.5LO



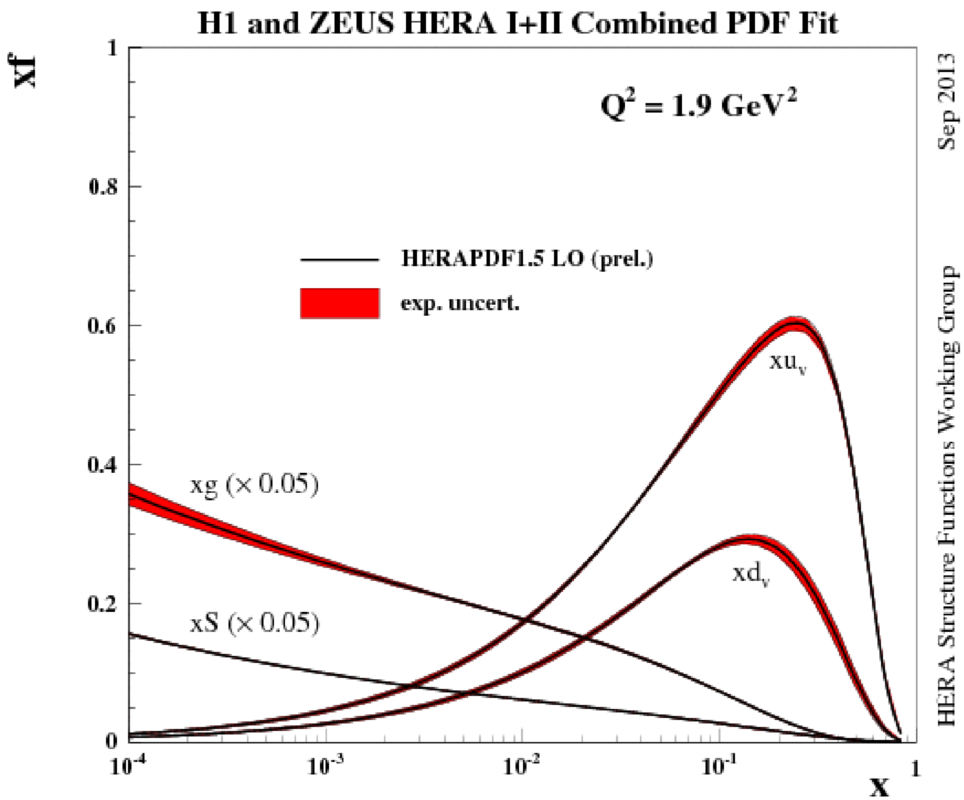
- Good description of low-x data even below the Q^2 cut of the fit ($Q^2_{cut} = 3.5$ GeV^2)

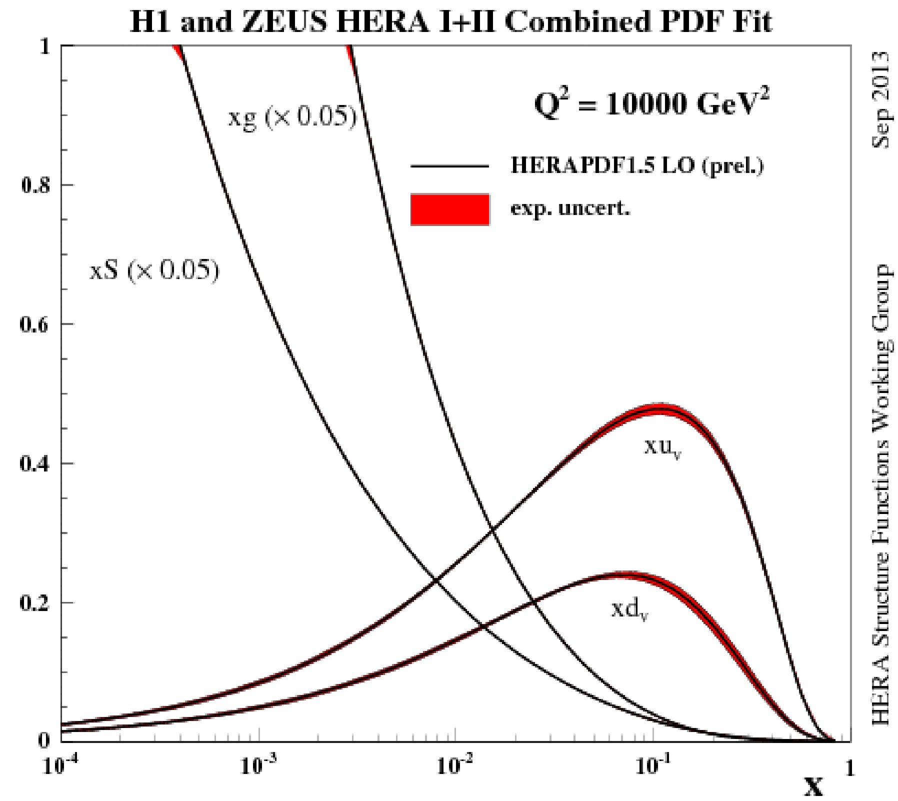
Comparison of high Q^2 NC and CC e^+p data with the HERAPDF1.5LO





PDFs from HERAPDF1.5LO

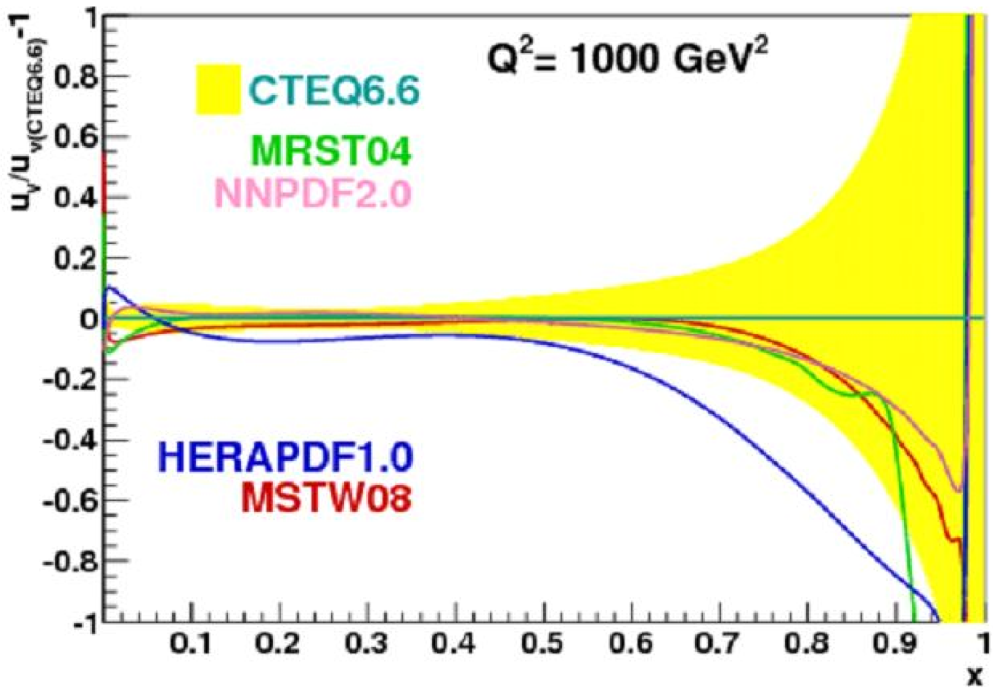




NC cross section at high x - motivation

- Most of the data available for x > 0.7 have been obtained in fixed-target experiments in a Q^2 range where pQCD may not be fully applicable

- The PDFs are poorly determined at high-x
- Large differences despite the fact that all fitters use the same parametrization $xq \sim (1-x)^{\beta}$

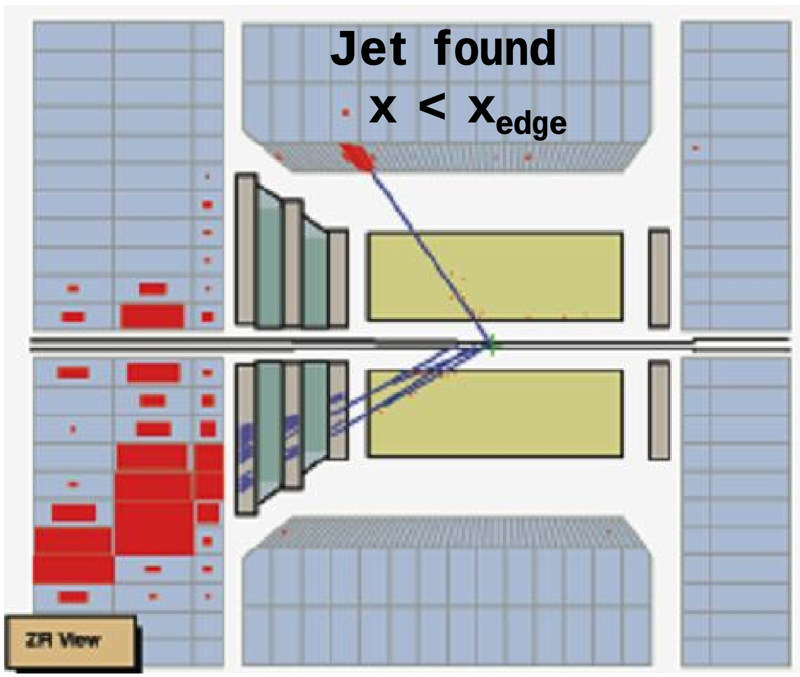


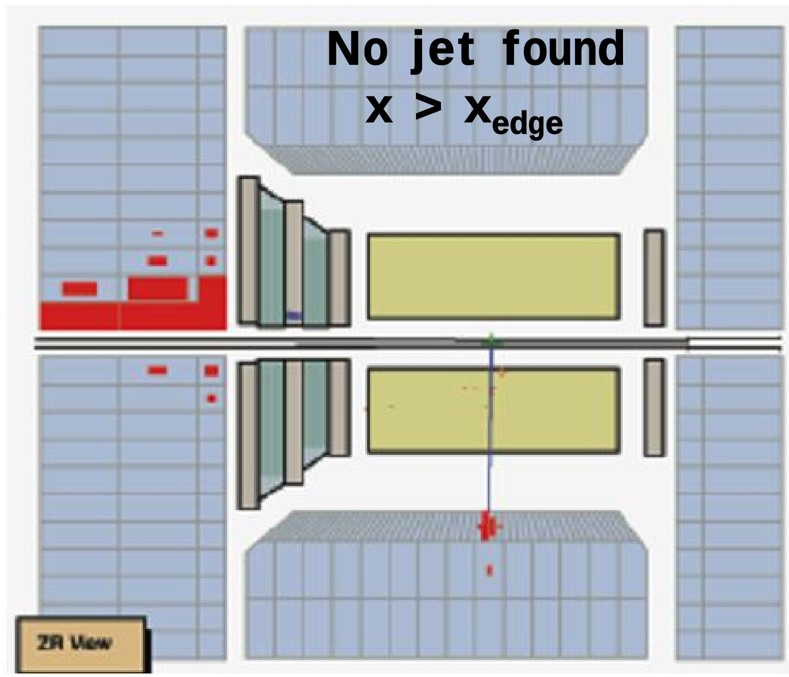
- HERA offered an opportunity to probe the large-x region, up to the kinematic limit at high Q^2 where pQCD and DGLAP evolution dynamics are applicable

- New measurement from ZEUS from high-x sector: **arXiv:1312.4438**

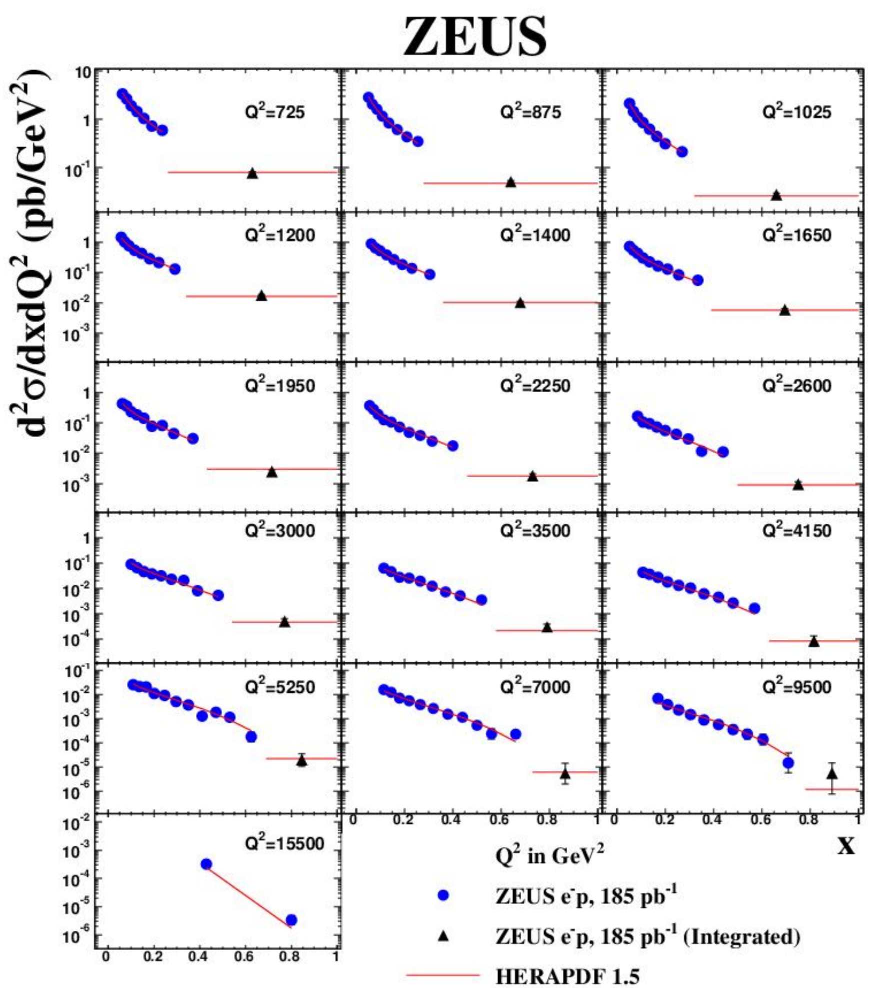
NC at high x – reconstruction method

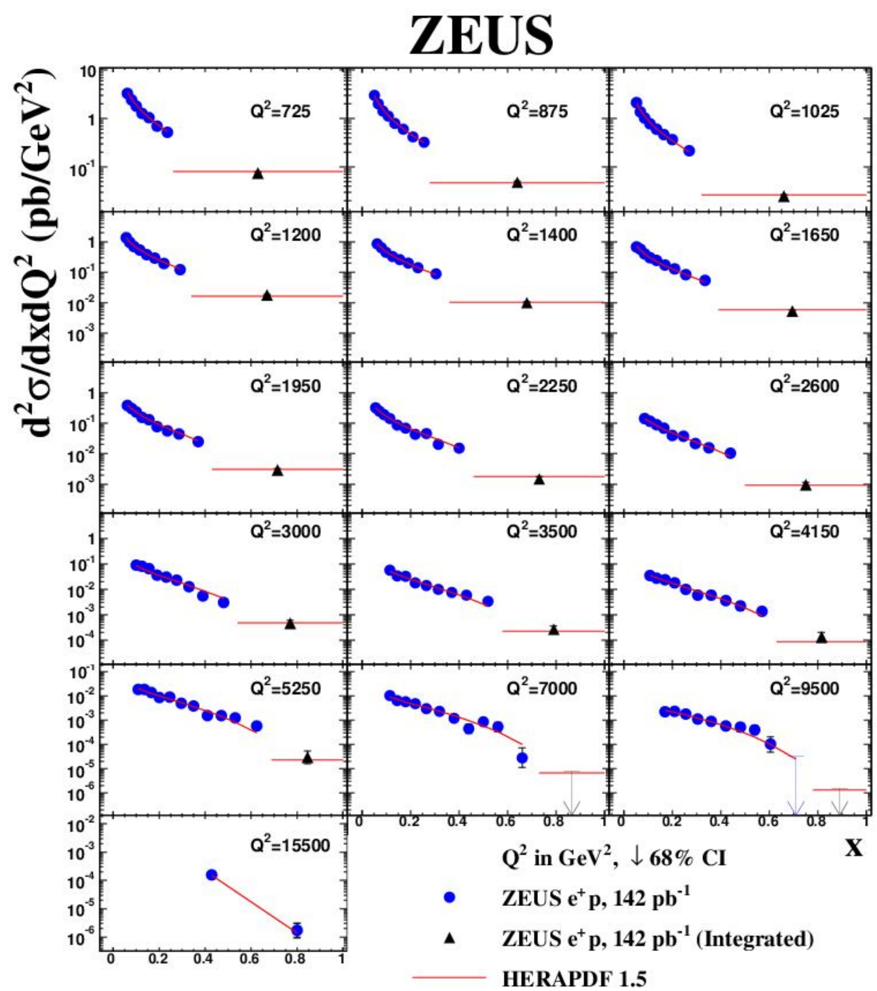
- At high Q^2, scattered electron seen with about 100 % acceptance
- As x increases and the jet associated with the struck quark disappears down the beam-pipe, the ability to reconstruct x is limited by the energy loss
- For not too high x – measure x from jet: $\frac{d^2\sigma(x,Q^2)}{dx\,dQ^2}$
- For $x > x_{edge}$ → measure $\int_{x_{edge}}^{1} \frac{d^2\sigma(x,Q^2)}{dx\,dQ^2}$ (the higher the Q^2, the higher x_{edge})
- $E_{T,jet}$ >10 GeV; Up to three jets allowed





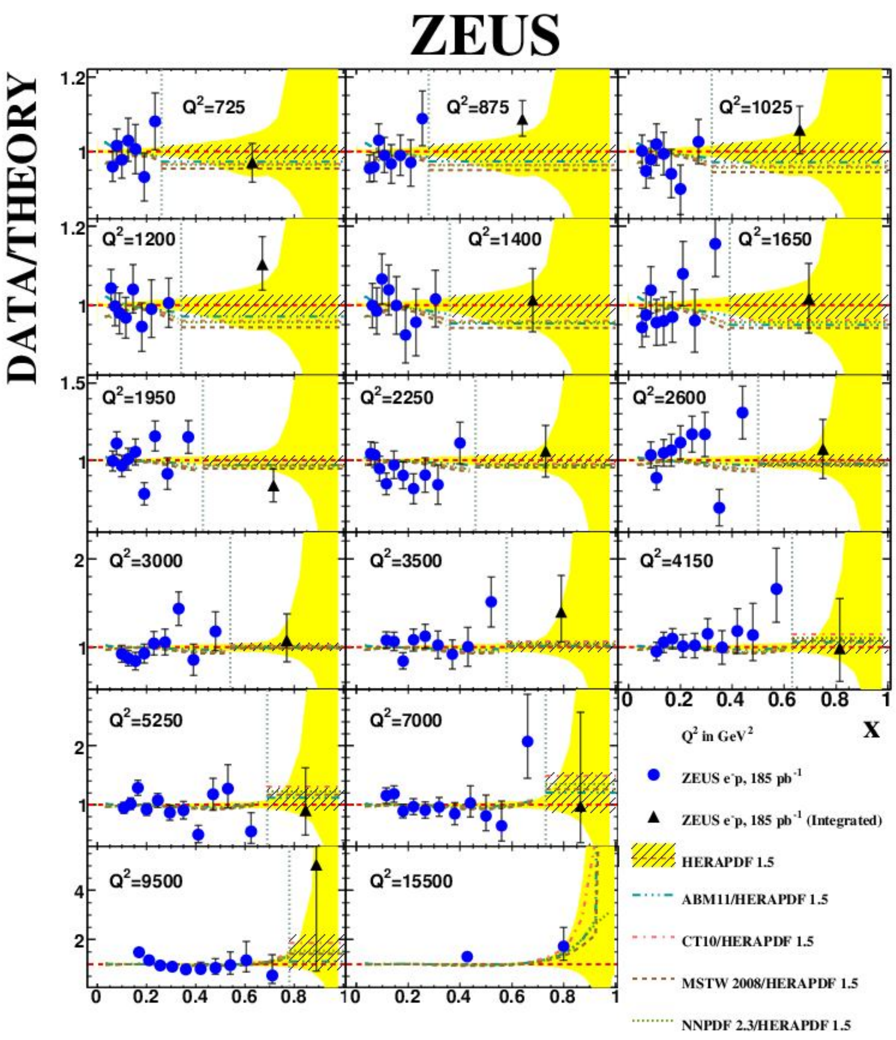
e^+p and e^-p NC cross sections

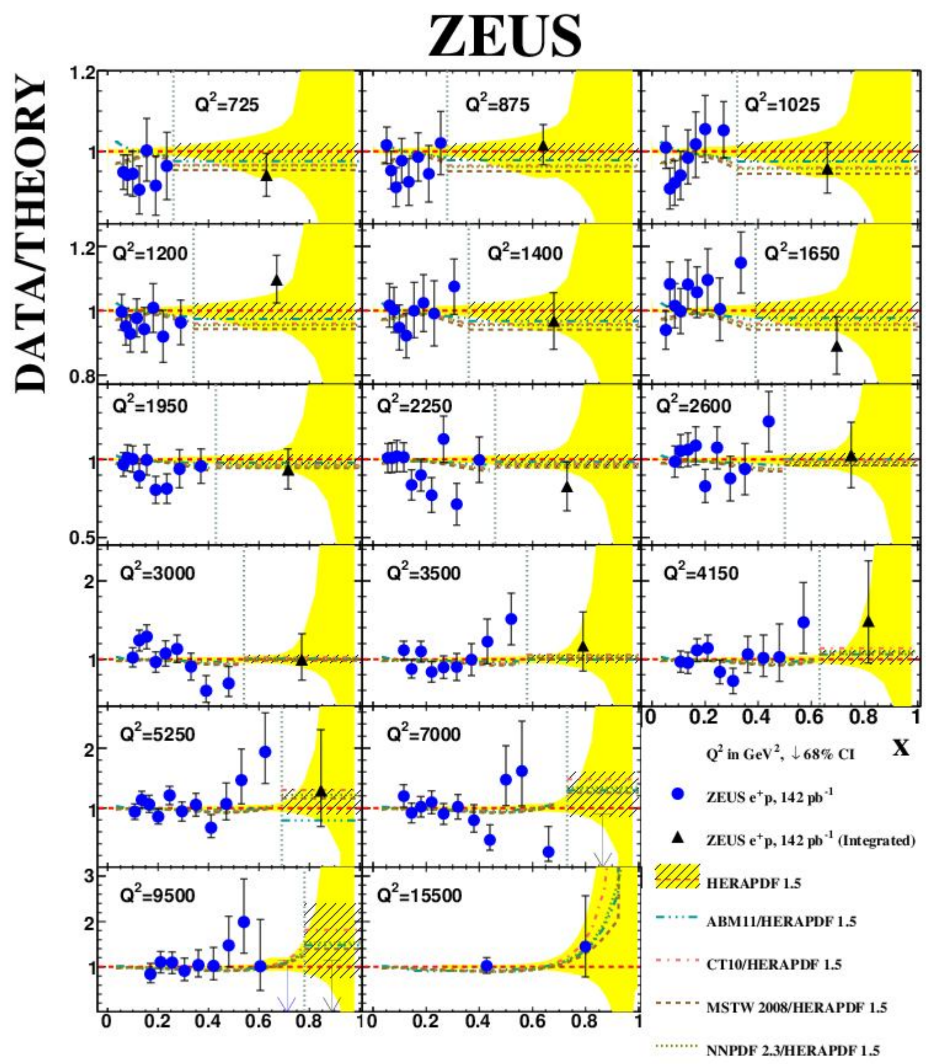




- The averaged integrated cross sections are plotted at $x = (x_{edge}+1)/2$
- Within the quoted uncertainties the agreement between measurements and expectations is good

The ratio of the measured cross sections to the HERAPDF1.5





- Predictions from other PDF sets are also normalised to the predictions from HERAPDF1.5

F_L measurement - motivation

- At NLO and NNLO QCD, analyses of DIS data constrain the gluon density through the precision measurements of F_2 and the reduced NC cross sections through their scaling violations

- The gluon density is directly related to F_L via the approximate relation

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

→ The direct measure of F_L can be used to demonstrate its sensitivity to the gluon density by comparing the gluon obtained from the F_L measurements to the predicted gluon density obtained from a NLO QCD fit to DIS data

- H1 and ZEUS have published F_L measurements at low and medium Q^2

➢ New measurement from H1 at medium and high Q^2 region: $6.5 \cdot 10^{-4} \leq x \leq 0.65$ for $35 \leq Q^2 \leq 800$ GeV^2 - **arXiv:1312.4821**

New measurements of NC σ_r at high y at different $\sqrt{s}$

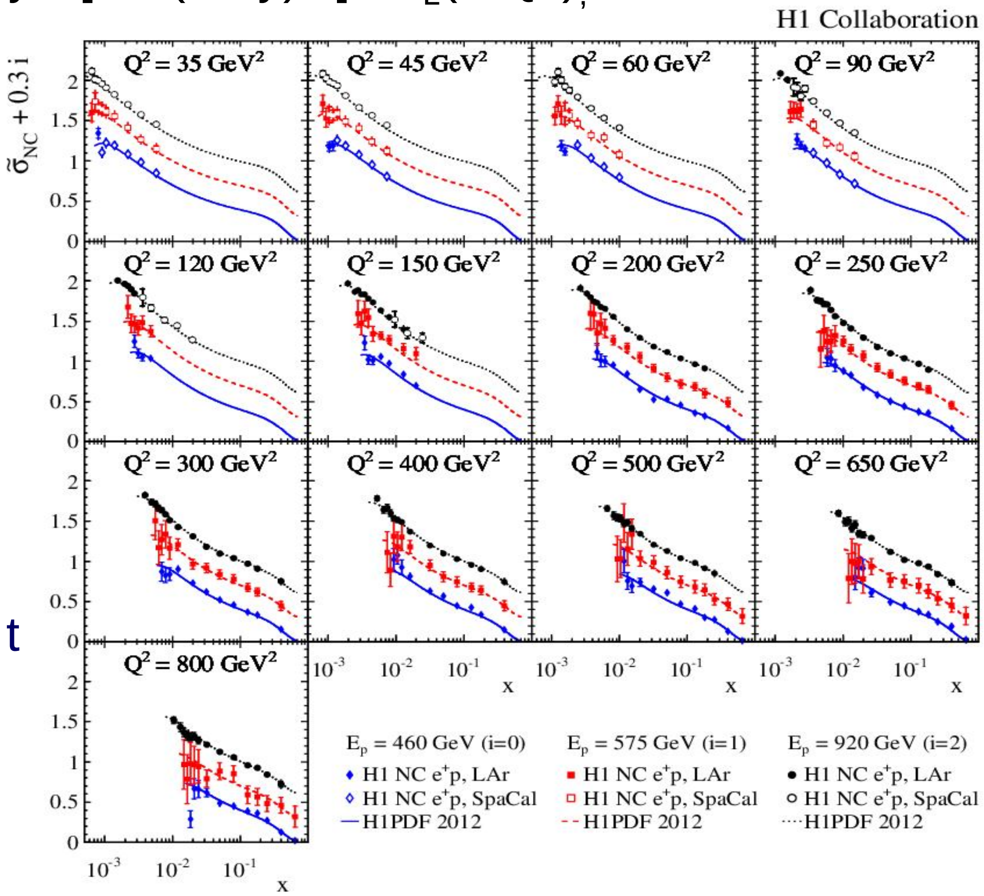
$$\sigma_r(x,Q^2) = F_2(x,Q^2) - y^2/[1 + (1-y)^2] \cdot F_L(x,Q^2),$$

- An experimental separation between the F_2 and F_L possible by providing a set of measurements at fixed x and Q^2 but at different values of y
- From HERA three sets of data:

  E_e = 27.6 GeV

  E_p = 920, 575 and 460 GeV

  → Measurements of σ_r for different values of $s \approx 4E_pE_e$ provide a separation of F_2 and F_L

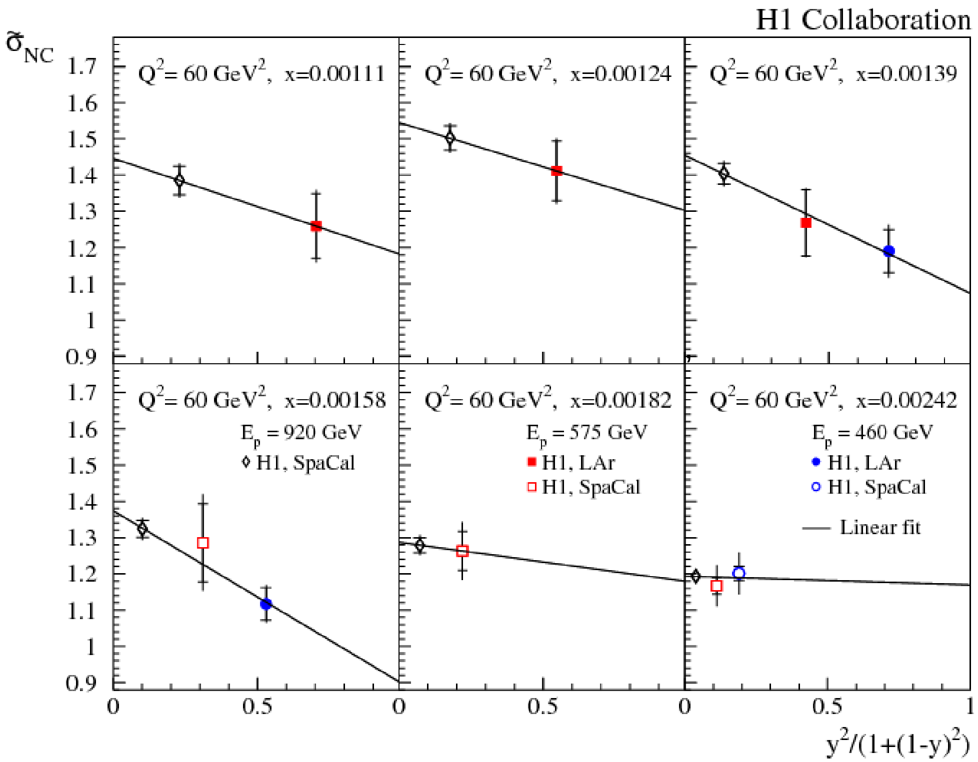


- The measurements are performed up to the highest accessible inelasticity of 0.85

F_L determination

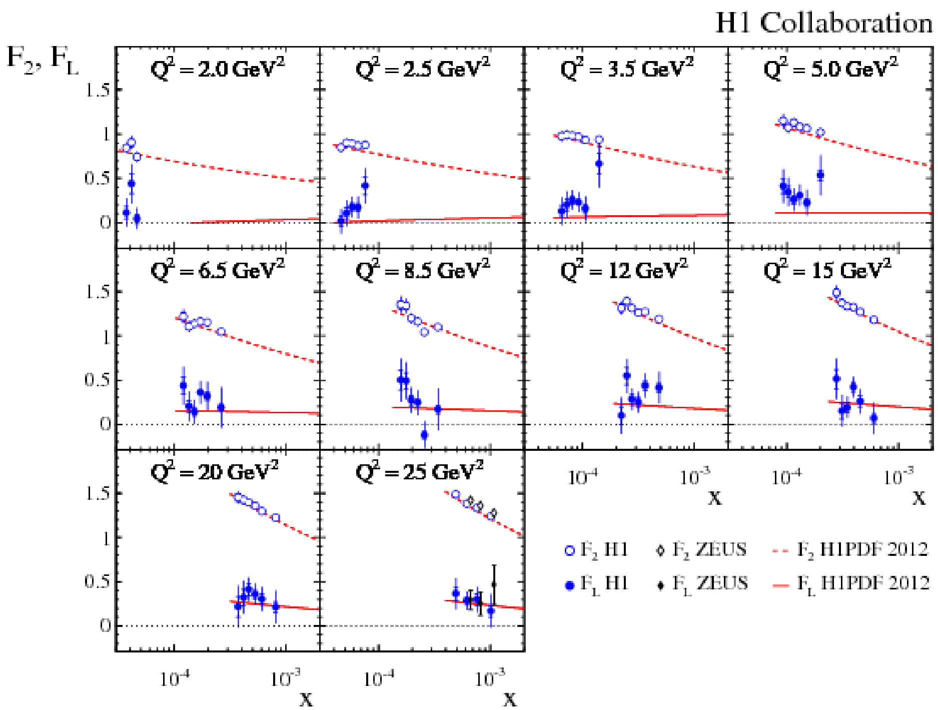
$\sigma_r = F_2 - y^2/[1 + (1-y)^2] \cdot F_L$

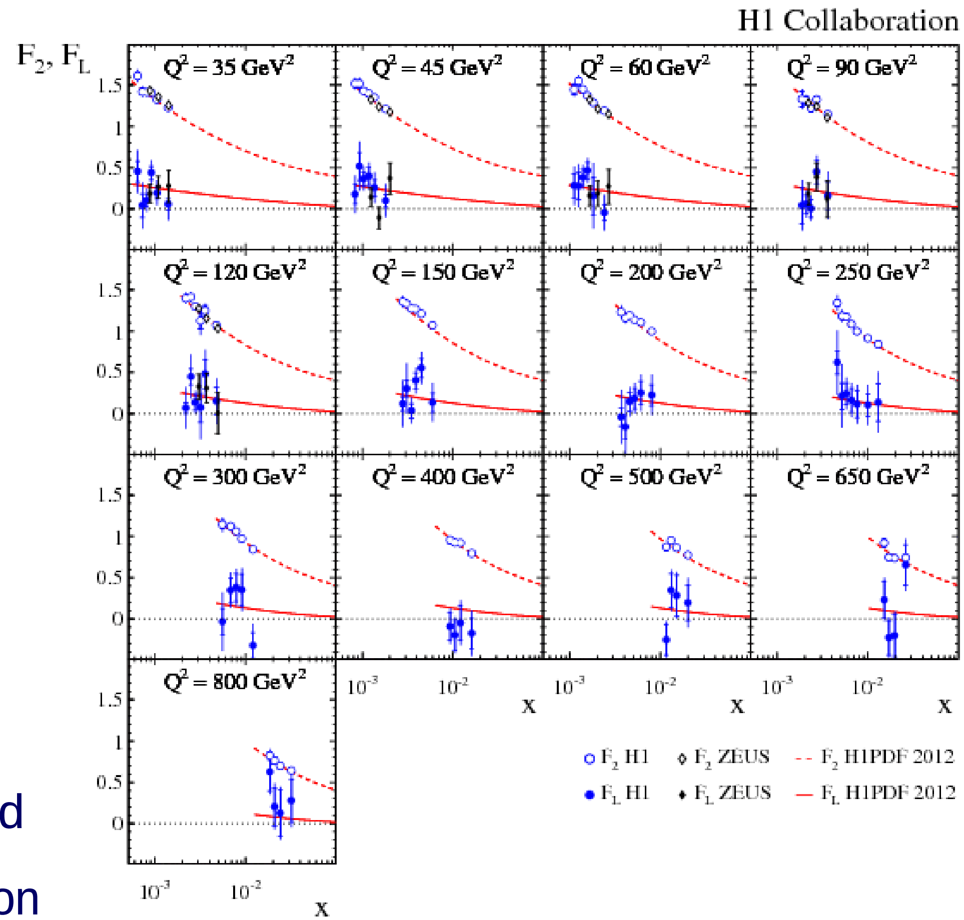
- F_L determined from measurements of σ_r at different s



- The negative slopes of the linear fits → the non-vanishing values of the F_L
- Determination procedure takes into account correlations due to syst. uncertainties
- A model independent method with no assumptions for the F_L and F_2

$F_L(x,Q^2)$ and $F_2(x,Q^2)$

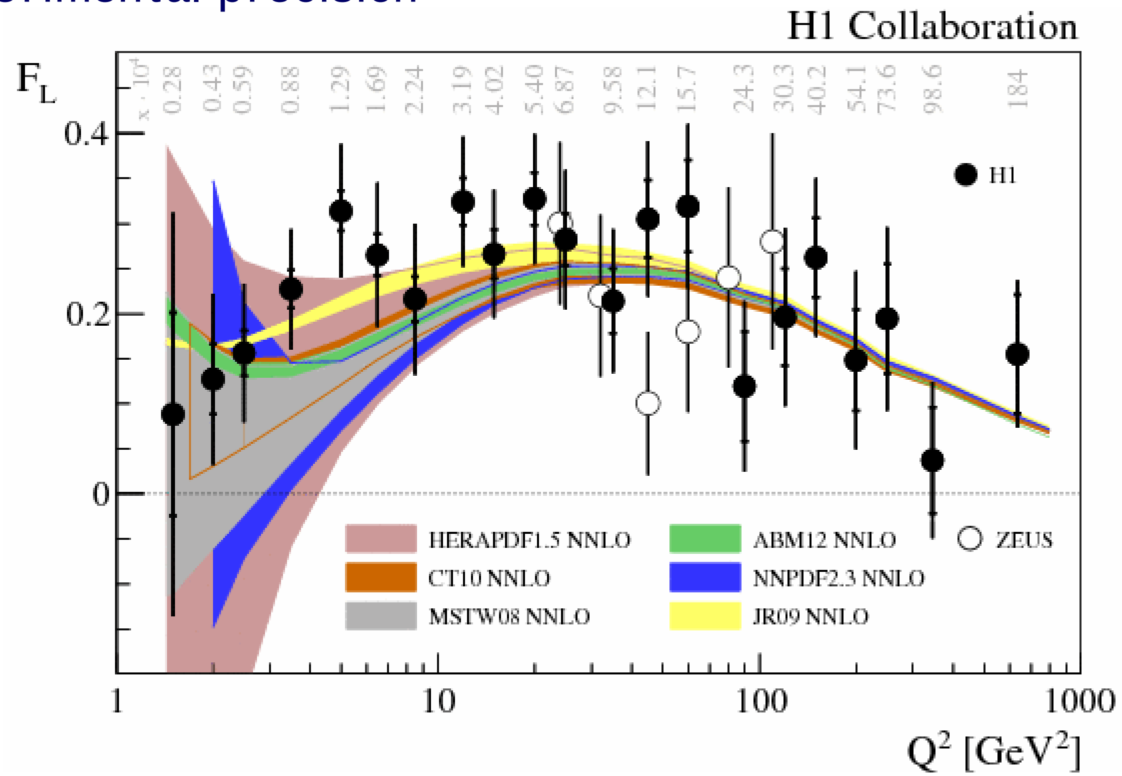




- Measurement of F_L from H1 completed
- Final results from ZEUS expected soon
- Measured HERA F_2 and F_L are consistent with predictions of the NLO DGLAP fit obtained from H1 data

F_L (Q^2) and different QCD predictions

- To reduce the experimental uncertainties the F_L measurements are combined at each Q^2 value and the highest Q^2 bins are averaged to achieve an approximately uniform experimental precision

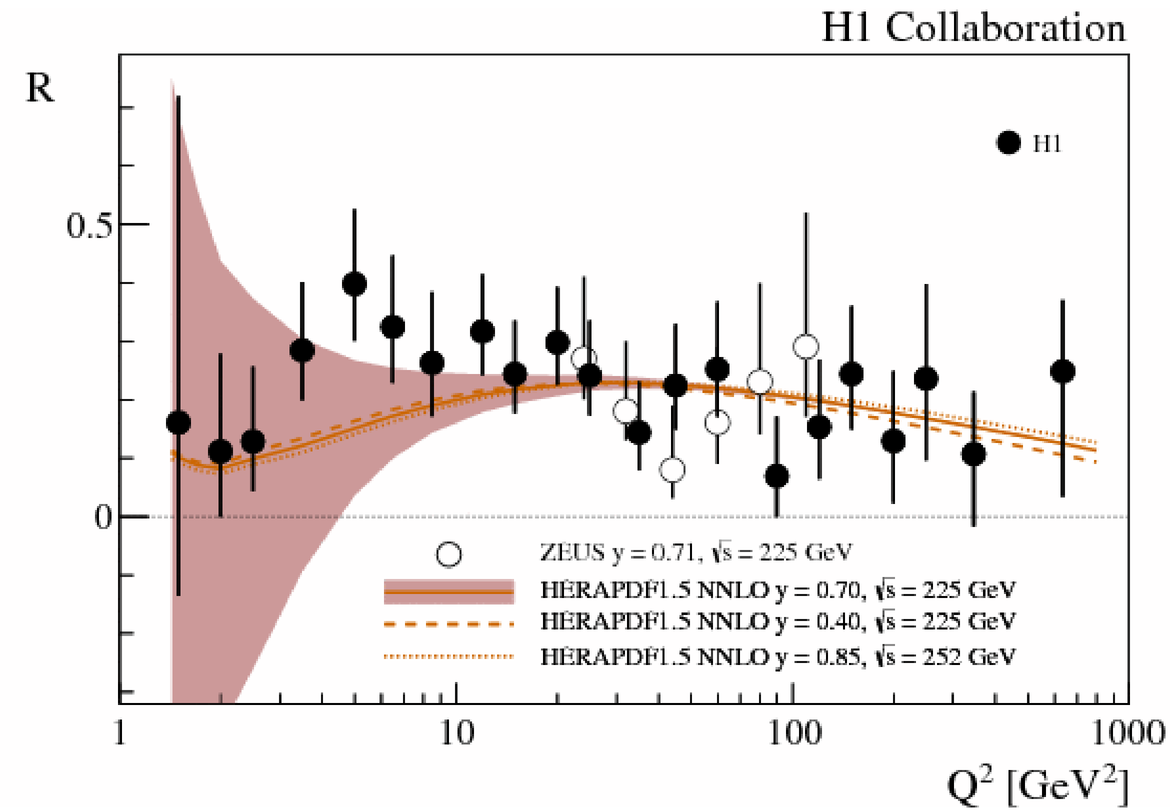


- Good agreement between H1 and ZEUS measurements
- Within the uncertainties all predictions describe the data reasonably well

Ratio $R(Q^2)$ compared to the HERAPDF1.5

$$R = \frac{\sigma_L}{\sigma_T} = \frac{F_L}{F_2 - F_L}$$

- The cross section ratio R of longitudinally to transversely polarised virtual photons



- Consistent with a constant value across the entire Q^2 range

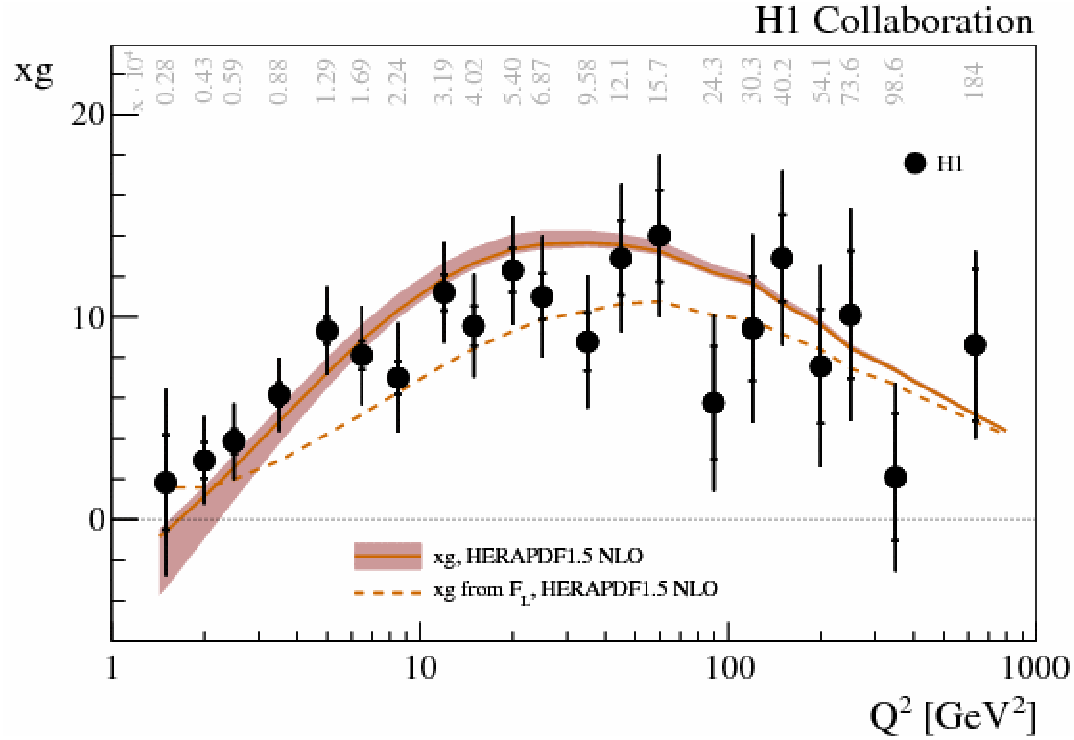
  R = 0.23 ± 0.04

  with χ^2/ndf =314/367

- Consistent with previously published H1 and ZEUS data

Gluon density $xg(Q^2)$

- xg directly from FL: $xg(x,Q^2) \approx 1.77 \frac{3\pi}{2\alpha_s(Q^2)} F_L(x,Q^2)$
- xg indirectly from scaling violations - from $\partial F_2/\partial \ln Q^2$



- A reasonable agreement between the gluon density as extracted from the direct measurement of F_L based on the approximate relation with the gluon derived indirectly from scaling violations

Summary

- New PDFs from HERA data obtained at LO – essential for LO MC generators
- New NC cross section measurements at high-x from ZEUS → will put constraints on PDFs at large x where PDFs are poorly determined
- New measurements of NC cross sections at high y and high Q^2 from H1 data
  - Simultaneous determination of F_2 and F_L without any model assumptions
  - Several NNLO QCD fits provide reasonable description of HERA F_L results
  - The ratio R of the longitudinally to transversely polarised virtual photon cross section is consistent with being constant over the kinematic range of the data
  - Gluon PDF extracted from the new measurement
    → gluon density extracted from a NLO approximation is found to agree reasonably well with the gluon determined from scaling violations

Backup

Averaging procedure

- Swim all points to a common x-Q^2 grid
- Moved 820 GeV data to 920 GeV p-beam energy
- Calculate average values and uncertainties
  χ^2 minimization in which the parameters are the true values of the cross section and the correlated systematic error parameters (arXiv:0904.0929)
- Evaluate "procedural uncertainties"

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

- Exploit differences between H1 and ZEUS in detectors, methods and systematics to "cross-calibrate" and to reduce the systematic uncertainties.

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

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

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

QCD analysis

- ❑ DGLAP analysis based only on the HERA data:

- no need for heavy target corrections

- no strong isospin assumptions

- ❑ Some parameters in parametrisation functions constrained by the number and momentum sum rules

$\sum$mom. = 1 $\int u_v\, dx = 2$ $\int d_v\, dx = 1$

Fitted PDFs: $xg, xu_v, xd_v, x\bar{U} = x\bar{u} + (x\bar{c}), x\bar{D} = x\bar{d} + x\bar{s} + (x\bar{b})$

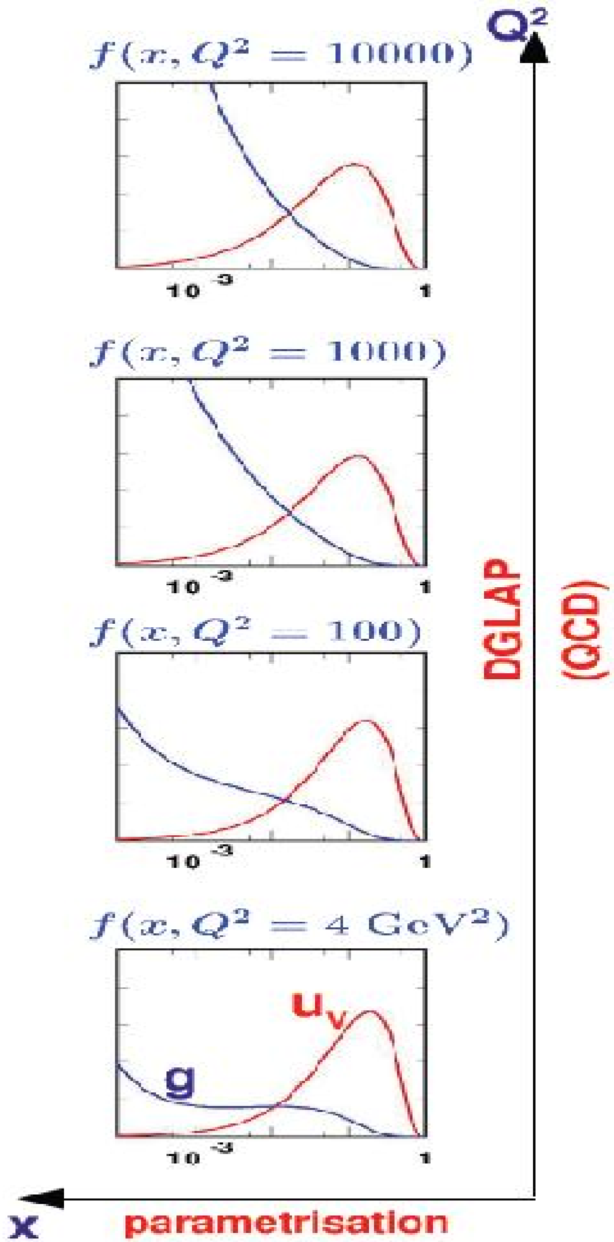
Uncertainties

- ❑ Experimental – using $\Delta\chi^2 = 1$ criterion

- ❑ Model – from variation of theory parameters:

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)]

- ❑ Parameterisation – from extra D, E, … terms in parameterisation



F_L determination

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

$f(y) = y^2 / [1 + (1 - y)^2\ ]$

μ_i – measured reduced cross section at x, Q^2 point i with a combined statistical and uncorrelated systematic uncertainty Δ_i

A set of nuisance parameters b_j for each correlated systematic error source j is introduced

The effect of correlated error sources j on the cross section measurements is given by the systematic error matrix $\Gamma_{i,j}$

$\chi^2/ndf = 184/210$