# The Structure of the Proton as Measured at HERA

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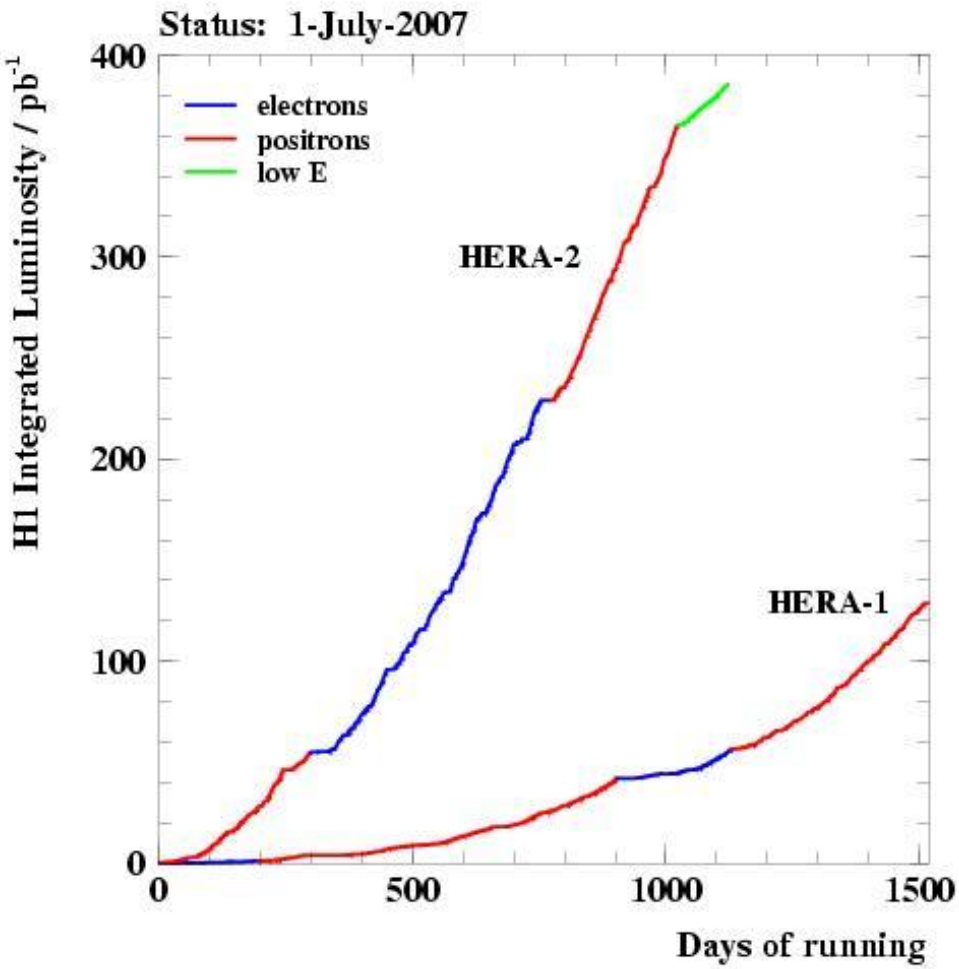
for the H1 and ZEUS Collaborations

- HERA+Experiments
- F2
- CC+xF3
- HERA QCD Fit
- FL

CIPANP, San Diego 25th-31th May, 2009

# HERA



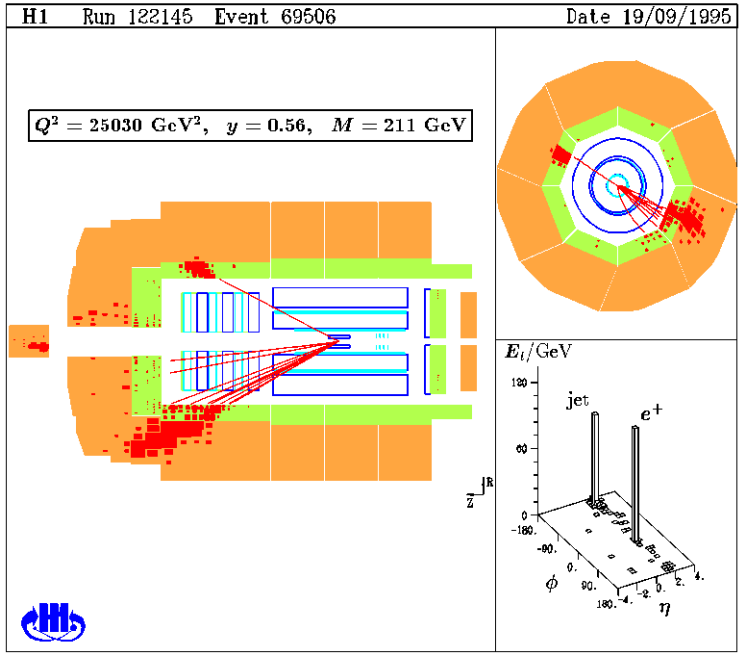

- In total ~500pb$^{-1}$ of high energy data collected in $e^-p$ and $e^+p$ modes
- CMS Energy $\sqrt{s}$=320 GeV
- Luminosity upgrade in 2001, detectors upgraded
- Low energy run for $F_L$ in 2007

# DIS events as seen in H1+ZEUS

Two Types of reaction possible
Neutral Current (NC) and Charged Current (CC)

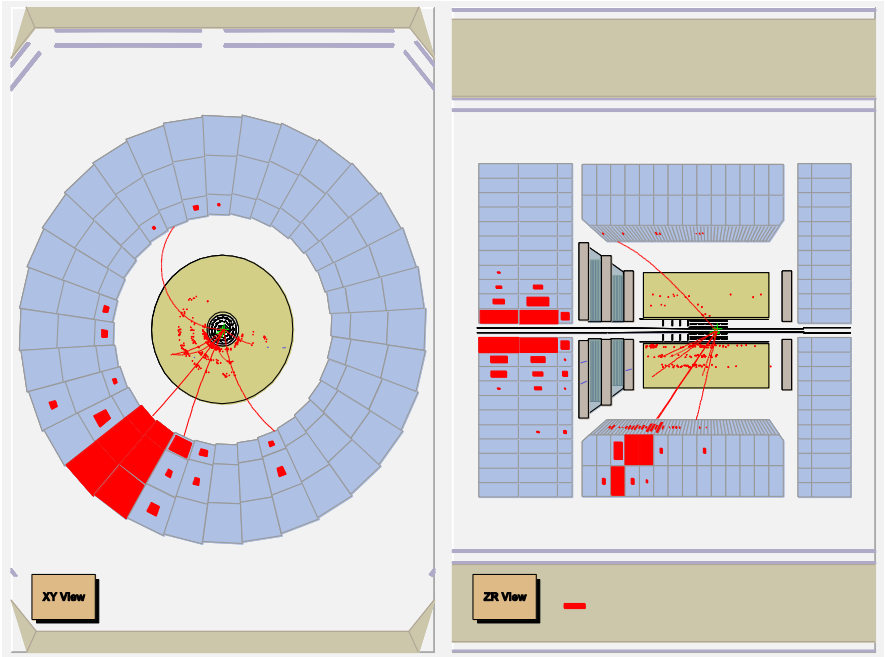
$$ep \rightarrow eX$$

$\gamma^*$, Z exchange

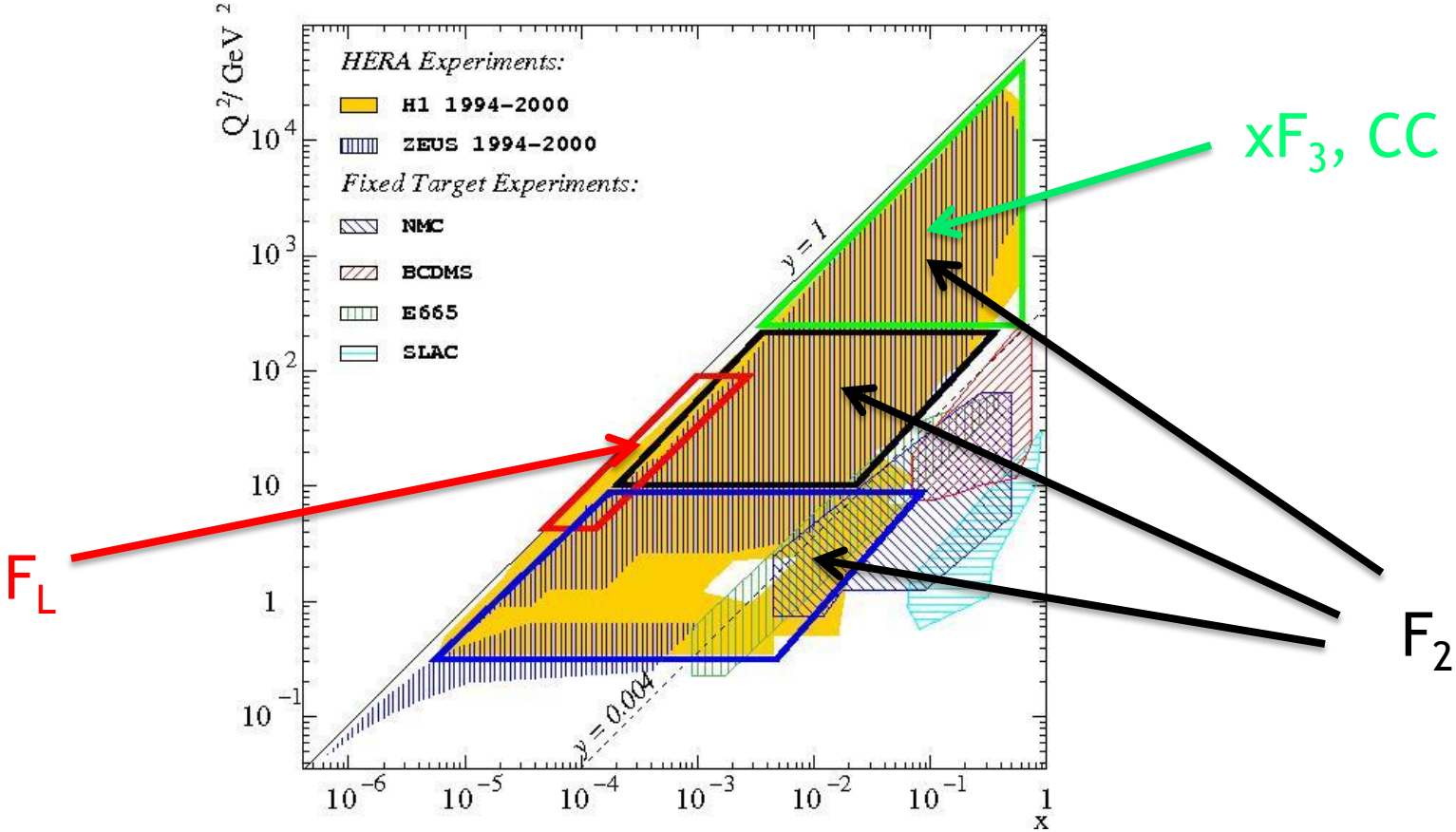



$$ep \rightarrow \nu X$$

W exchange



# The kinematic plane




- $Q^2$ is square of momentum transfer of $\gamma^*$, Z, W
- x is fraction of proton's momentum carried by struck quark
- y is inelasticity parameter $Q^2 = sxy$

# Deep inelastic scattering

NC: Sensitive to all quarks, valence quarks and gluon

$$\frac{\mathrm{d}^2\sigma^{\pm}_{NC}}{\mathrm{d}x\mathrm{d}Q^2} = \frac{2\alpha\pi^2}{xQ^4}\left[Y_+\tilde{F}_2 \mp Y_- x\tilde{F}_3 - y^2\tilde{F}_L\right] \qquad Y_\pm = \tfrac{1}{2}(1 \pm (1-y^2))$$

$$\tilde{F}_2 \propto \sum_i e_i^2 (xq_i + x\bar{q}_i)$$ All quarks at LO. Gluon from scaling violations.

$$x\tilde{F}_3 \propto \sum_i xq_i - x\bar{q}_i$$ Valence quarks

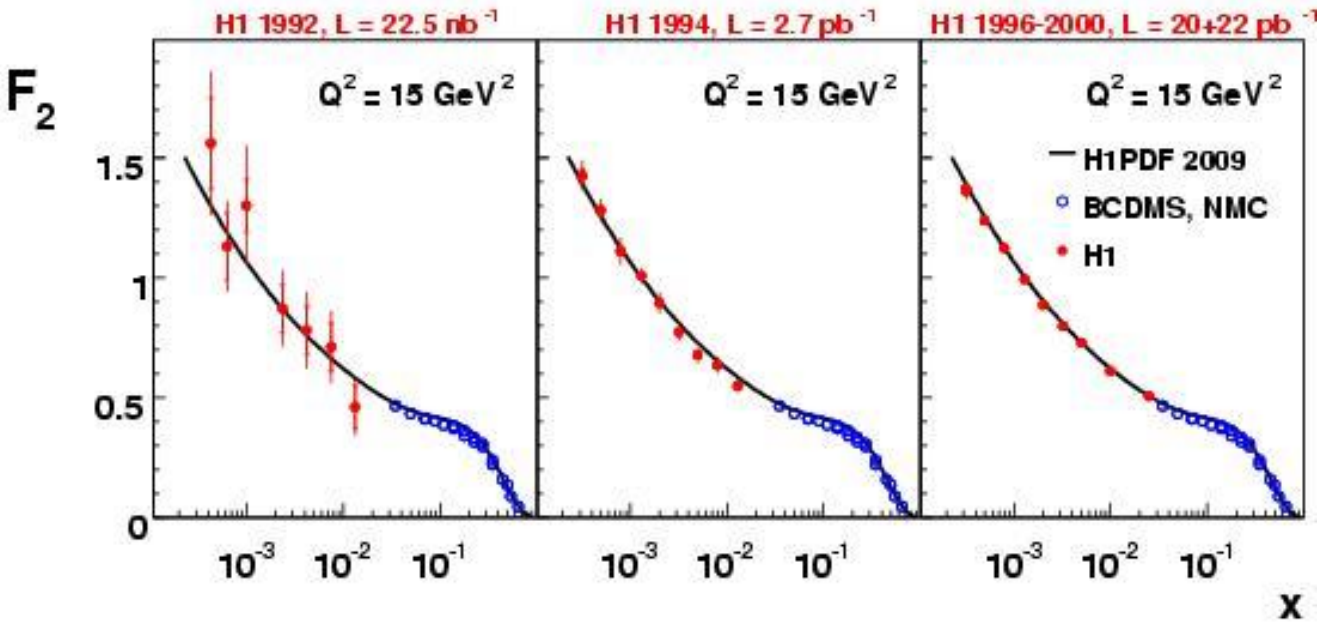
$$\tilde{F}_L \propto \alpha_s xg$$ Gluon at NLO

Use 'reduced cross section' to remove kinematic dependence:

$$\sigma_r = \frac{xQ^2}{2\alpha\pi^2 Y_+}\frac{\mathrm{d}^2\sigma^{\pm}_{NC}}{\mathrm{d}x\mathrm{d}Q^2} \approx \tilde{F}_2$$

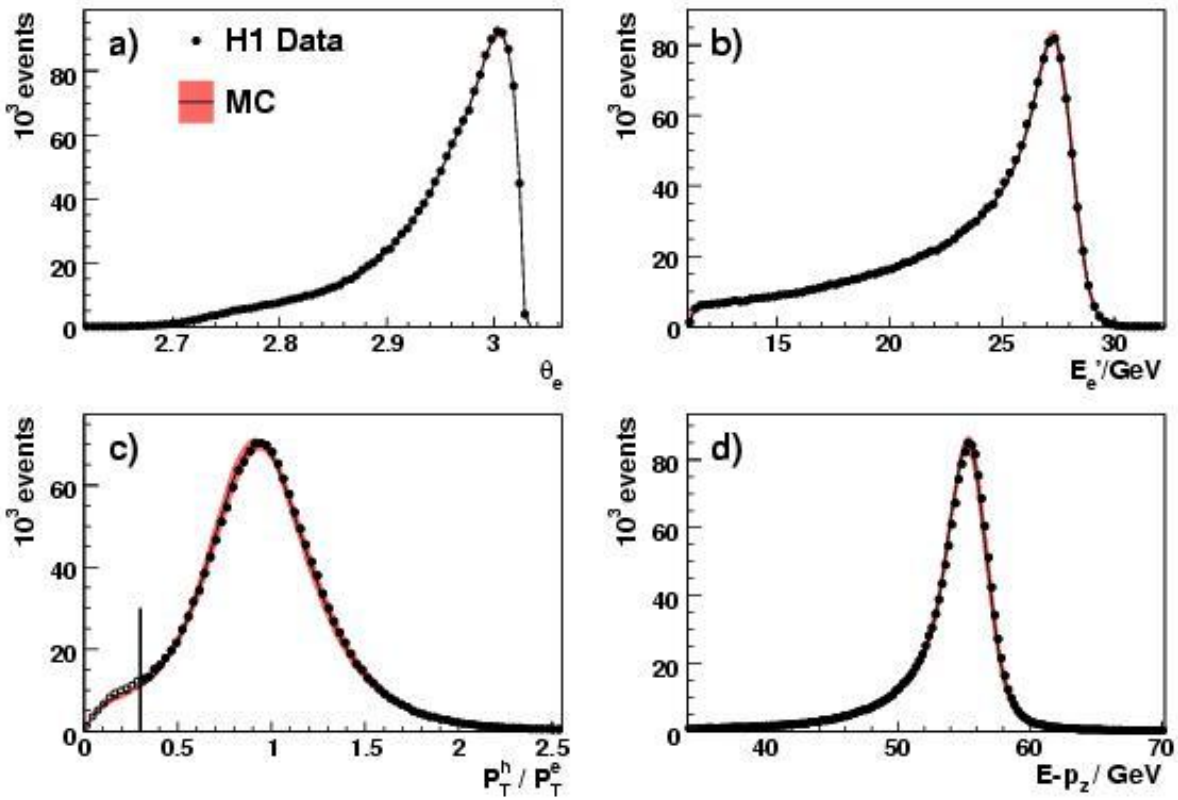
# $F_2$ at medium $Q^2$

Majority of DIS data is sensitive to $F_2$.
Most accurately measured structure function.
New measurement from H1 of HERA I data gives best precision so far achieved



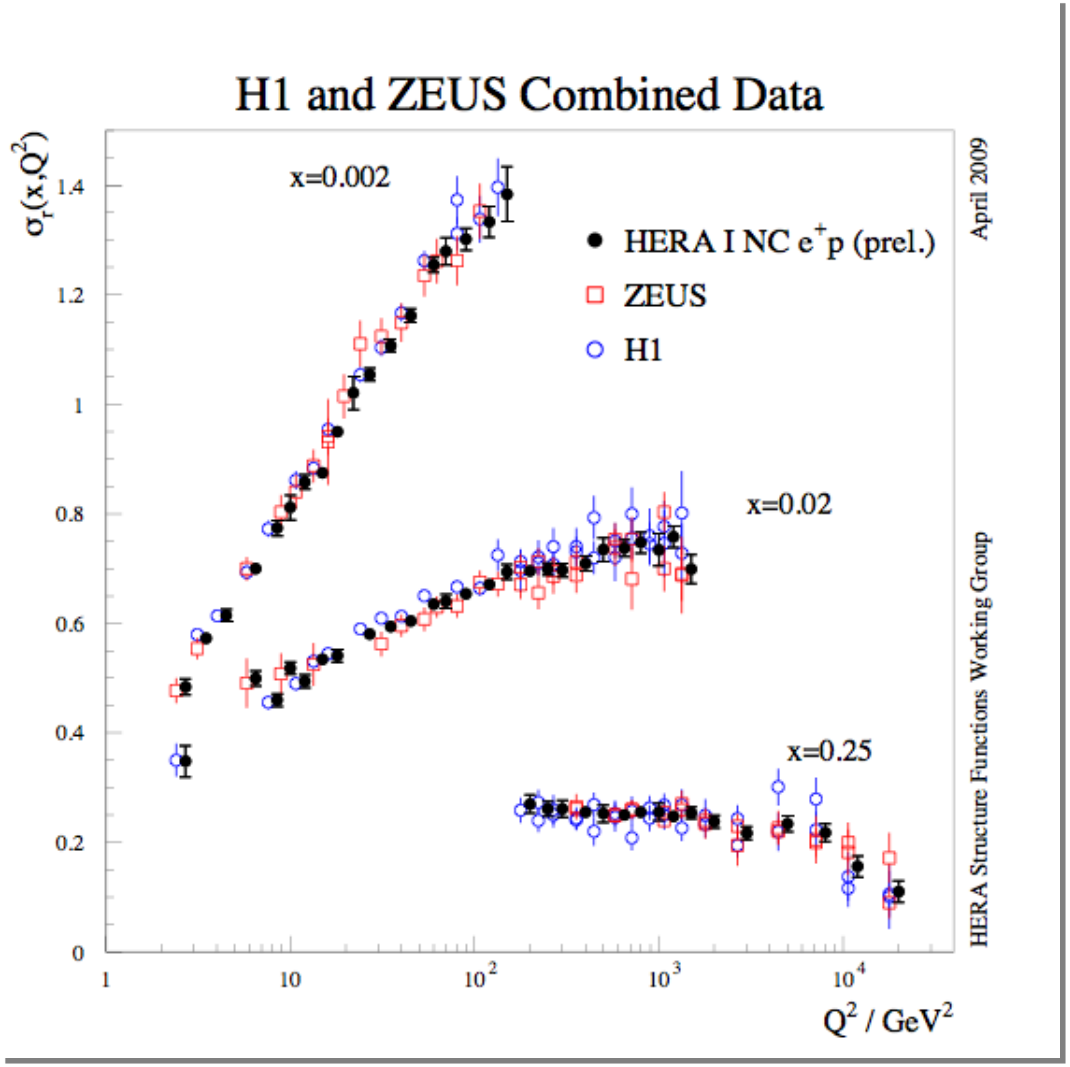

Accuracies improved to 1.3%-2%

# Technical control plots




Accuracy achieved by careful calibration of scattered electron and hadronic final state, using over-constraint of kinemtics

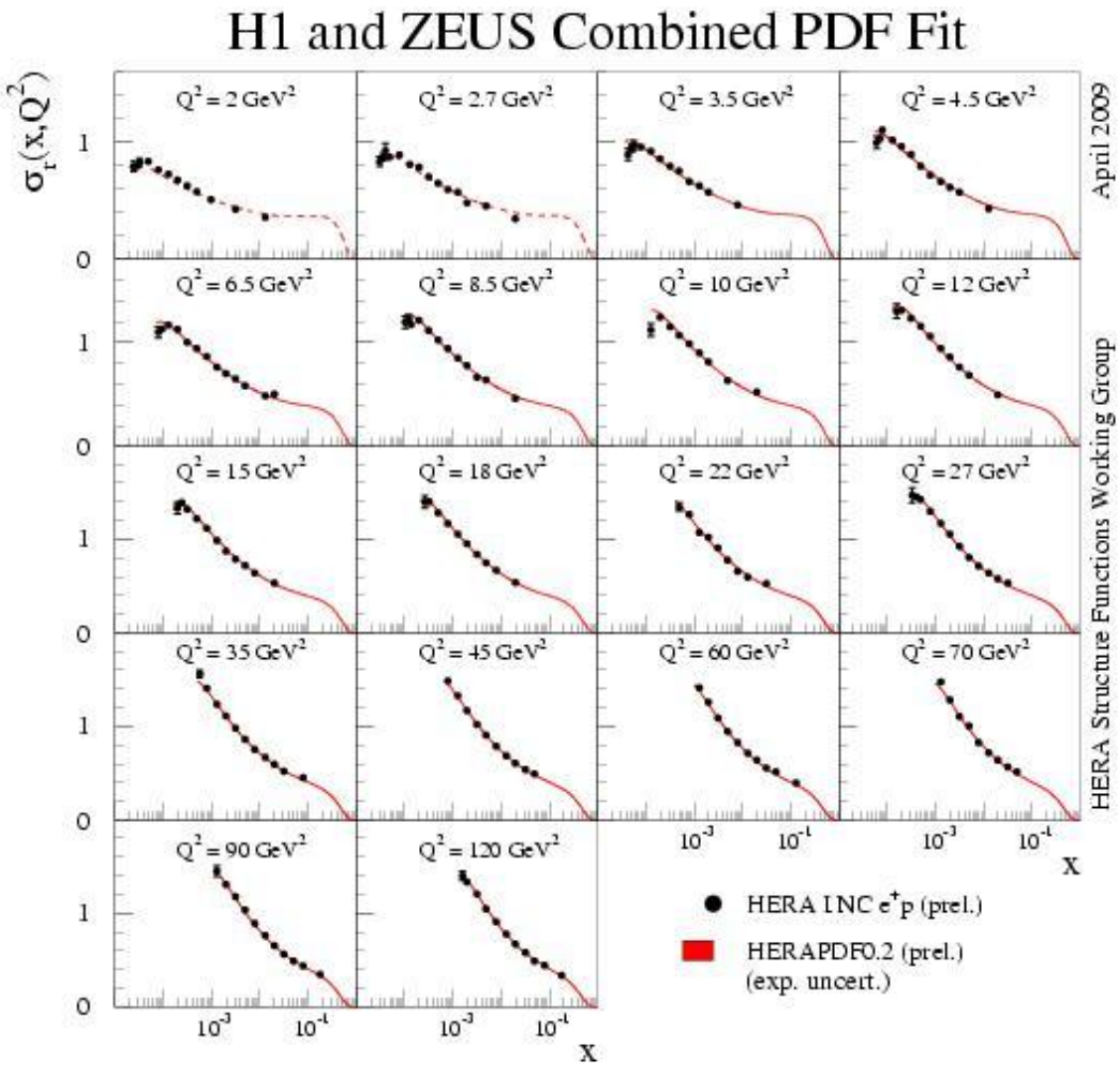
# Combination of H1+ZEUS




Can improve accuracy further by combining all H1+ZEUS data

Different systematic errors of the two experiments help cross calibrate and reduce the errors further

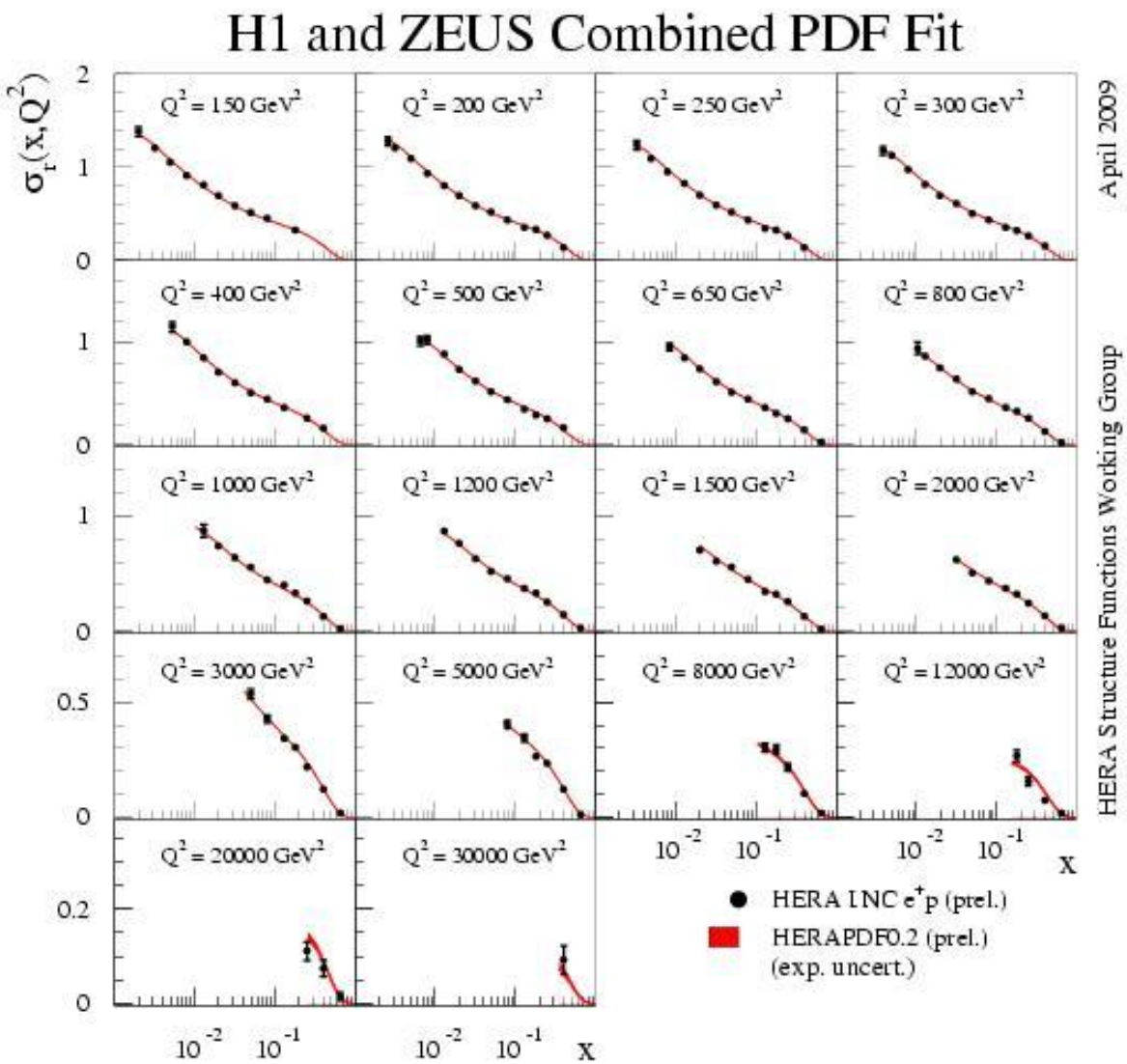
# $F_2$ at medium $Q^2$




Combination give 1% precision in this region

$F_2$ shows a steep rise towards low x. Well described by QCD fit (see later).

# $F_2$ at high $Q^2$



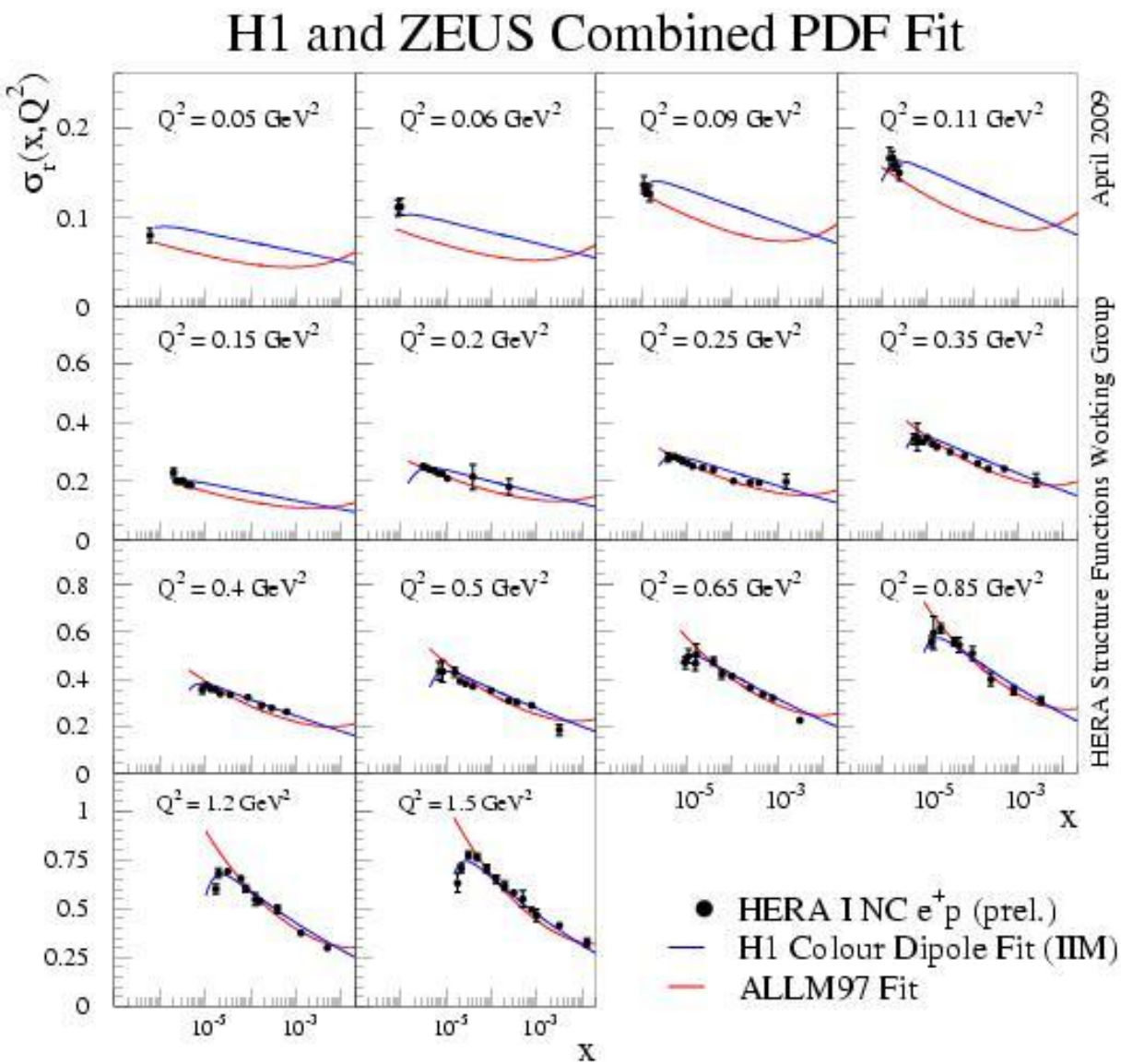

Data shown in the high $Q^2$ region.

Measurements up to 30000 GeV$^2$.

Rise of $F_2$ persists up to the highest $Q^2$.

Data well described by QCD fit from $Q^2$=3.5 to 30000 GeV$^2$.

# $F_2$ at low $Q^2$

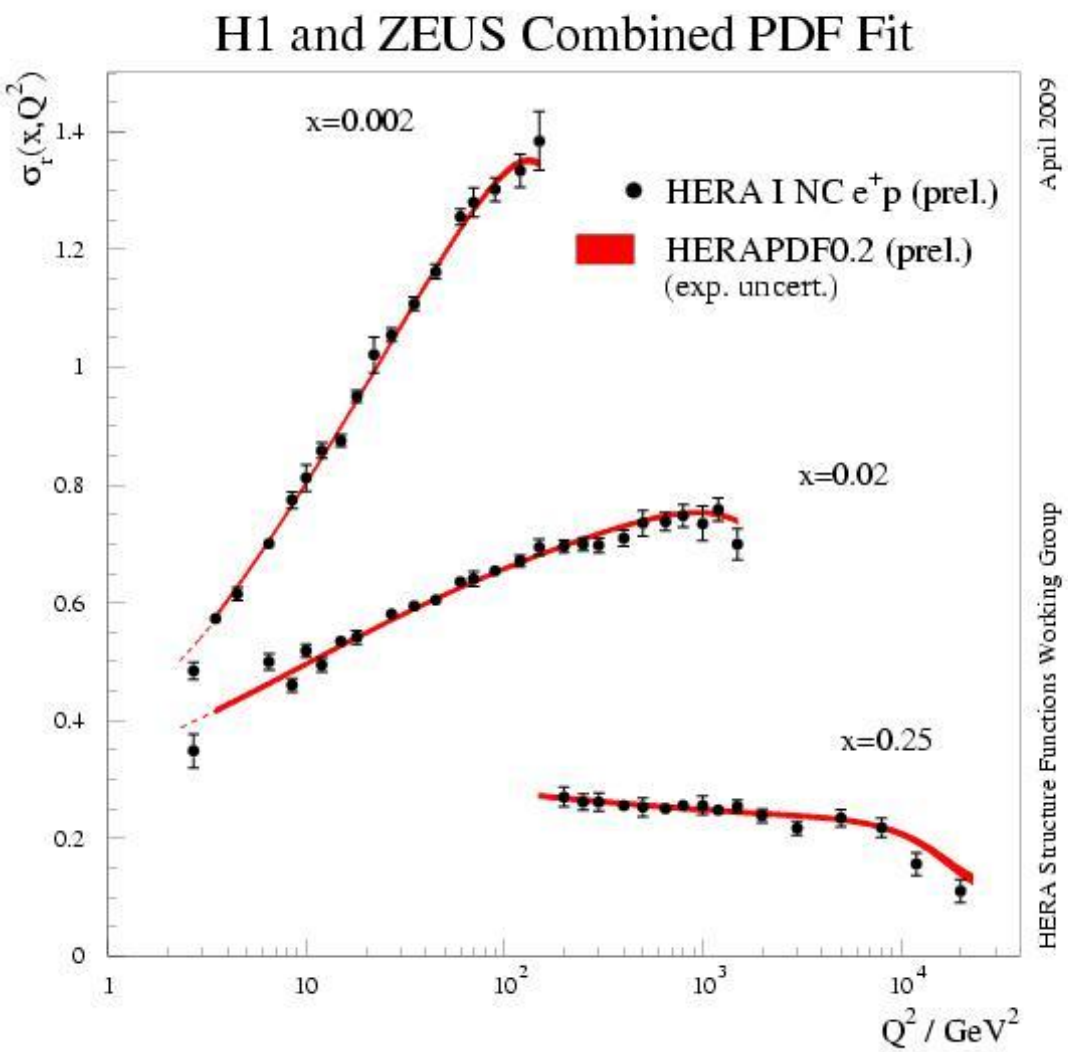



Data shown in the low $Q^2$ region.

pQCD not expected to work in the very low $Q^2$ region.

QCD inspired models do a reasonable job at describing data

# F2 as a function of $Q^2$




Plot data vs $Q^2$

Data show strong scaling violations at low x

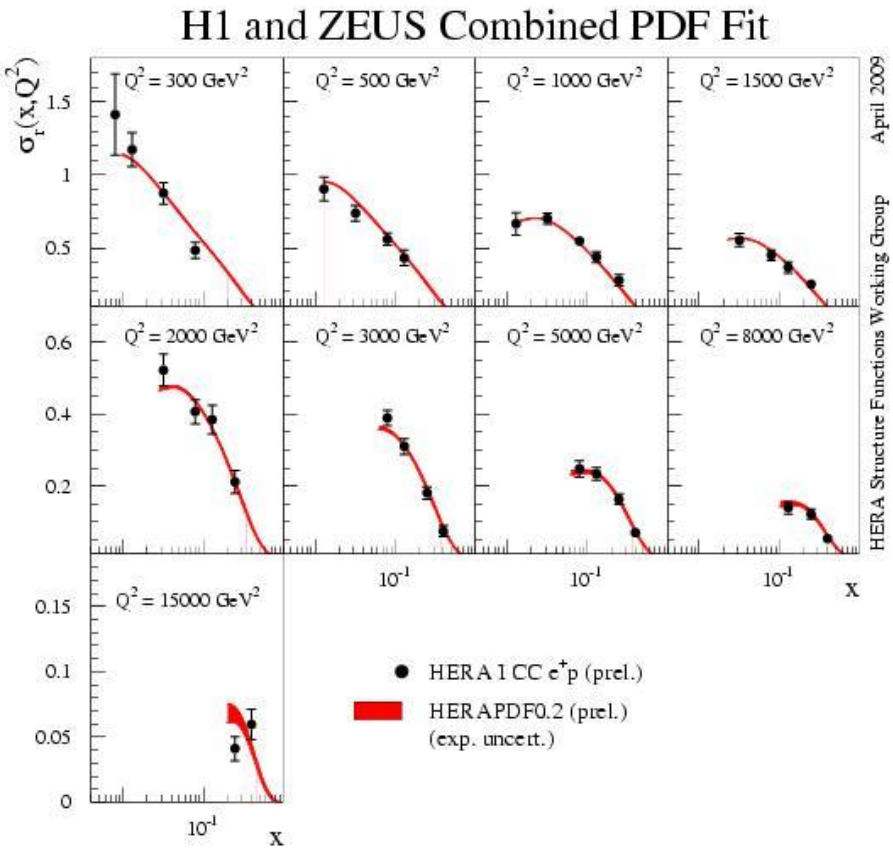
These are used to constrain the gluon:

$$\left(\frac{\partial F_2(x,Q^2)}{\partial Q^2}\right)_x \propto \alpha_s x g(x,Q^2)$$

# Charge Current data

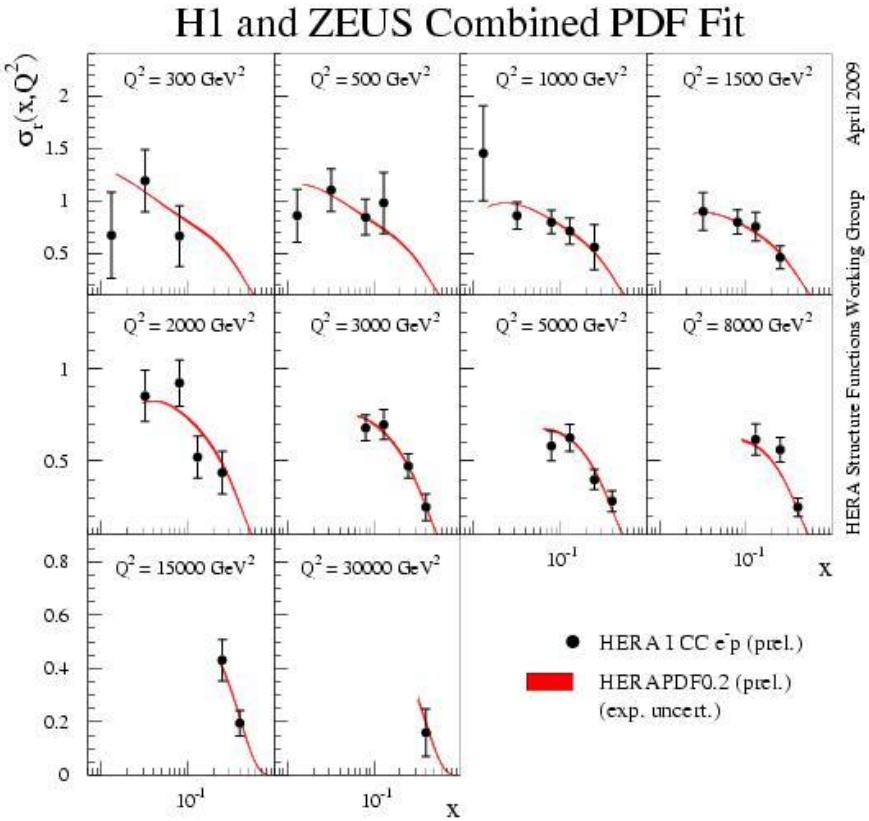
$e^+p$

$$\sigma_r \propto \left[ \bar{u} + \bar{c} + (1-y)^2 (d+s) \right]$$



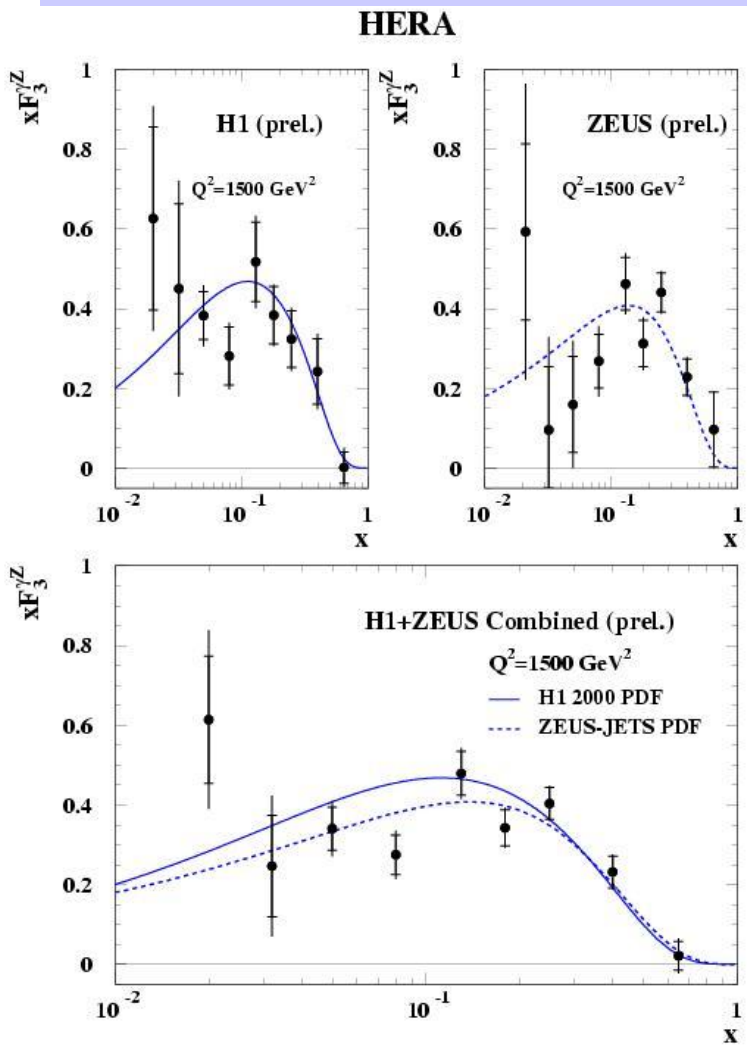

$e^-p$

$$\sigma_r \propto \left[ u + c + (1-y)^2 (\bar{d} + \bar{s}) \right]$$




CC $e^+p$ is sensitive to d density, which is not constrained well by NC

# $xF_3$




- $xF_3$ is extracted from the difference between the e+p and $e^-p$ NC cross-sections
- It is sensitive only to the valence quarks
- Measured by H1+ZEUS and combined to make most precise measurement at low x
- Sensitive to differences between fits

More on High Q2 CC+NC, see talk by Gerhard Brandt

# New HERA QCD Fit

- Fit uses combined H1+ZEUS NC, CC data only. No fixed target data.
- HERA jet data is not used in present fit, but has previously shown to improve g density

- Fit perform at NLO
- Parameterize parton distribution functions at starting scale and evolve with $Q^2$.

- Calculations now use the Thorne-Roberts Variable Flavour Number Scheme: an improved theoretical treatment of heavy quarks that takes the quark masses into account

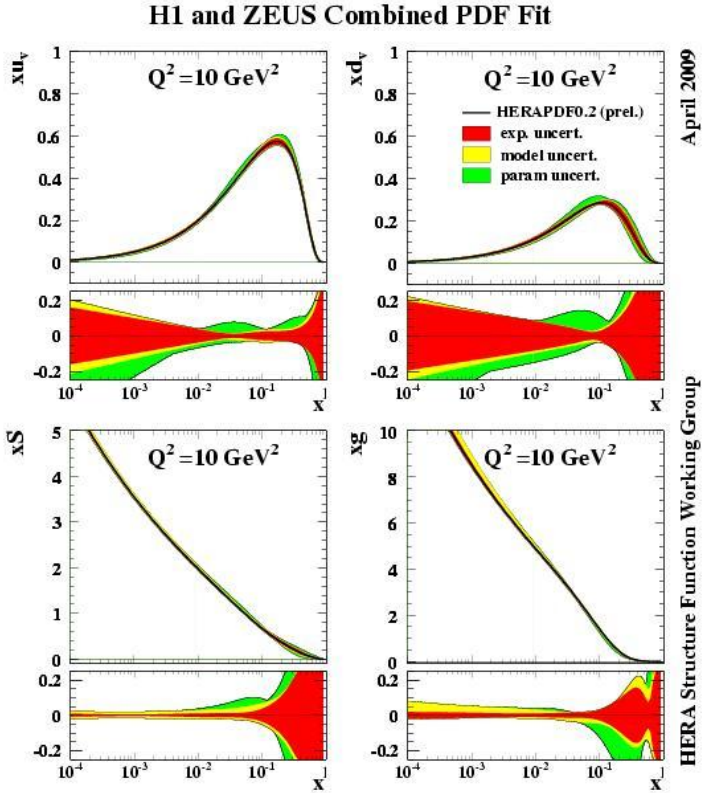
- Starting scale $Q^2_0 < M_c^2$ so $Q^2_0 = 1.9$ GeV$^2$
- Fix *s* density (no good constraints from HERA data)

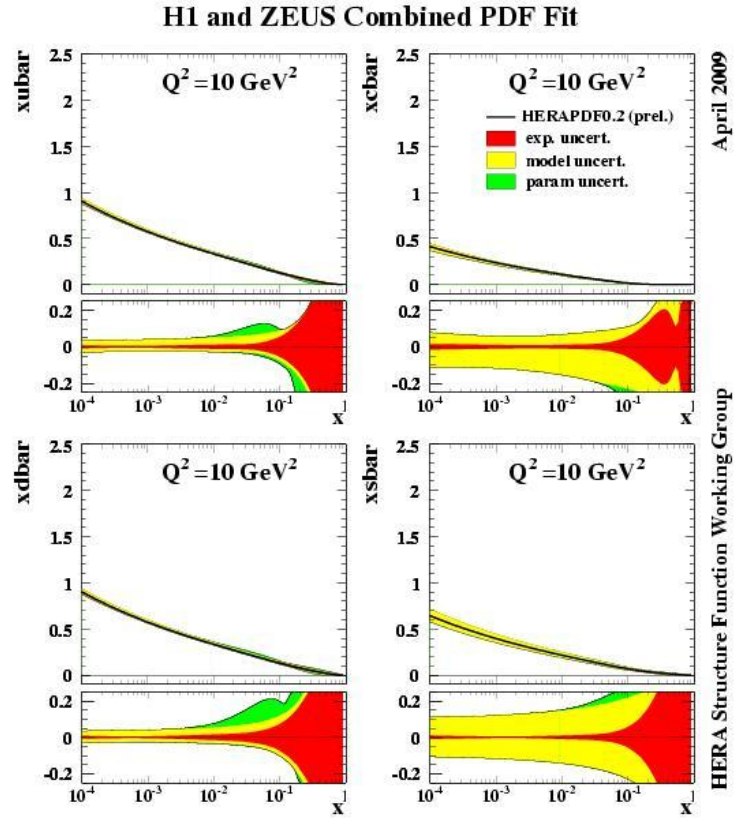
| | HERAPDF0.2 |
|---|---|
| Scheme | TR-VFNS |
| Evolution | QCDNUM17.02 |
| Order | NLO |
| $Q_0^2$ | 1.9 GeV$^2$ |
| $f_s = s/D$ | 0.31 |
| $f_c = c/U$ | 0.00 |
| Renorm. and Fact. scales | $Q^2$ |
| $Q^2_{min}$ | 3.5 GeV$^2$ |
| $\alpha_S(M_Z)$ | 0.1176 |
| $M_c$ | 1.4 GeV |
| $M_b$ | 4.75 GeV |

# QCD Fit Uncertainties

- Experimental uncertainty:
  Take into account experimental errors including, correlations bin to bin and between experiments/datasets
- Model uncertainty includes theoretical errors:
  - $M_c$ 1.35 →1.5 GeV, $M_b$ 4.3→5.0 GeV
  - strangeness s/D 0.23→0.38
  - $Q^2_0$ 1.5→2.9 $GeV^2$
  - Minimum $Q^2$ cut on data 2.5→5.0 $GeV^2$
- Parameterisation uncertainty:
  Vary parameterisation of PDFs at starting scale

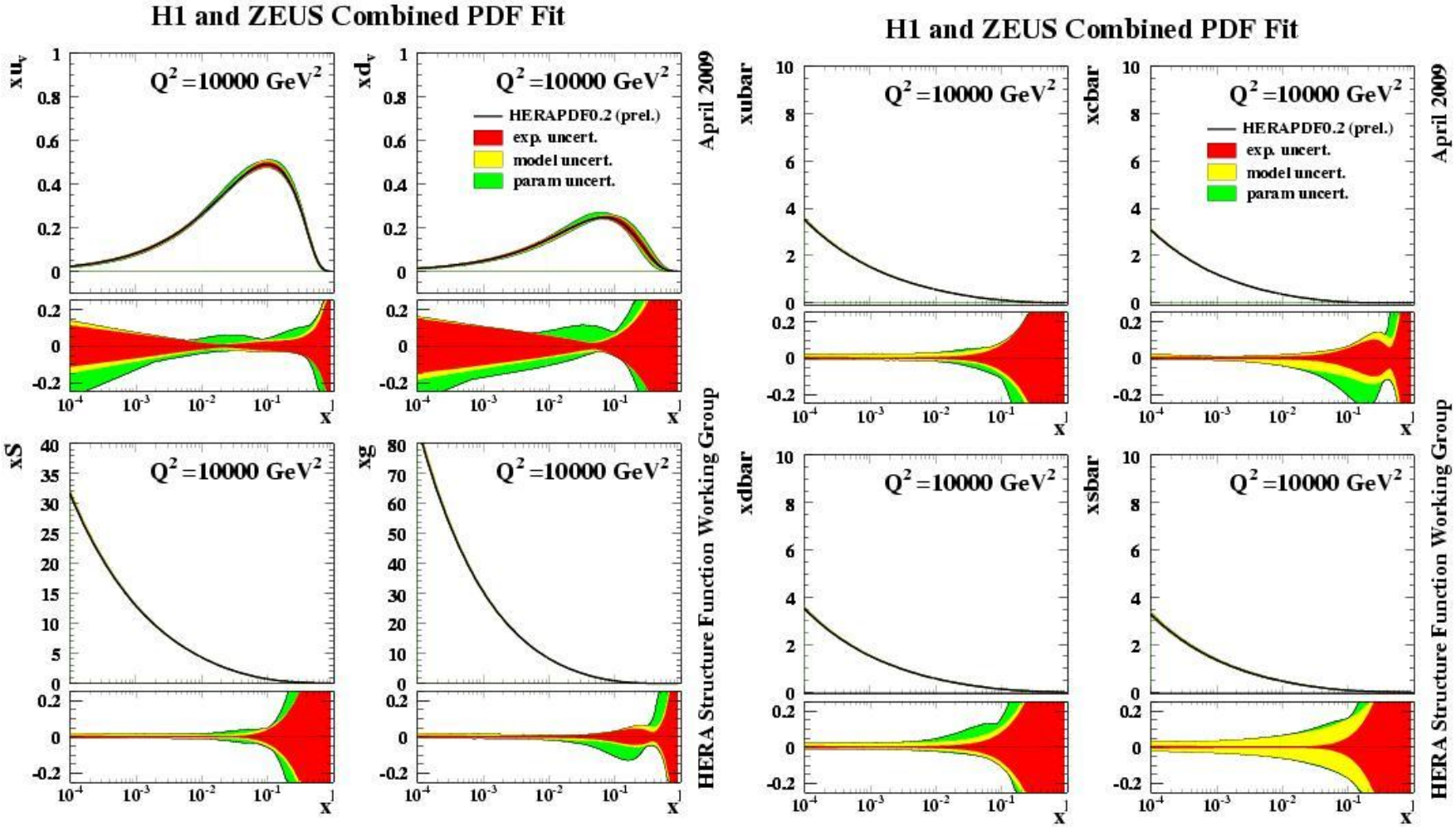
# HERA QCD fit $Q^2$=10 $GeV^2$



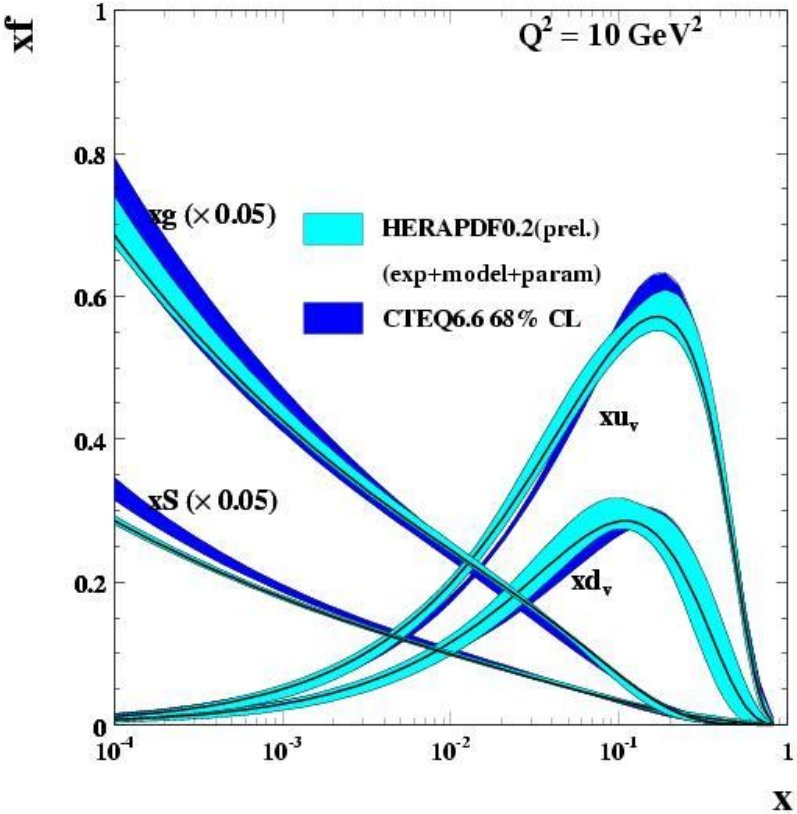

- Impressive precision for sea and gluon at low x
- Reasonable precision for valence at high x
- Gluon error relatively large at high x
- Model uncertainty large for charm at $Q^2$=10 $GeV^2$
- Strange not constrained by HERA data

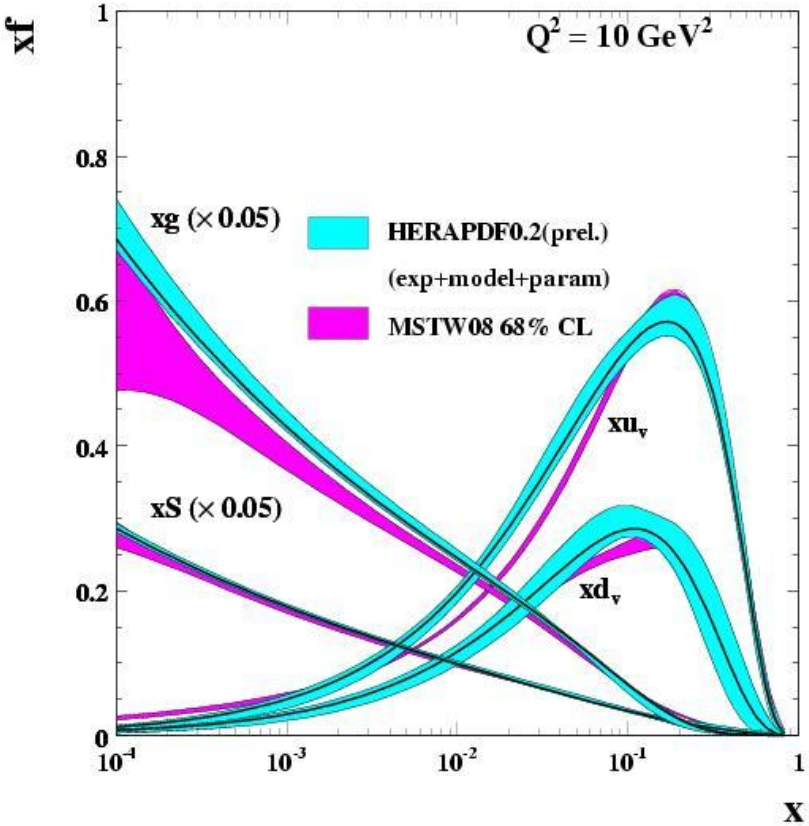
# HERA QCD fit at high $Q^2$




- QCD evolution generally means a reduction of theory errors
- Impressive errors on PDFs at LHC energies
- Enables precision predictions for LHC cross sections

# Comparison with global fits



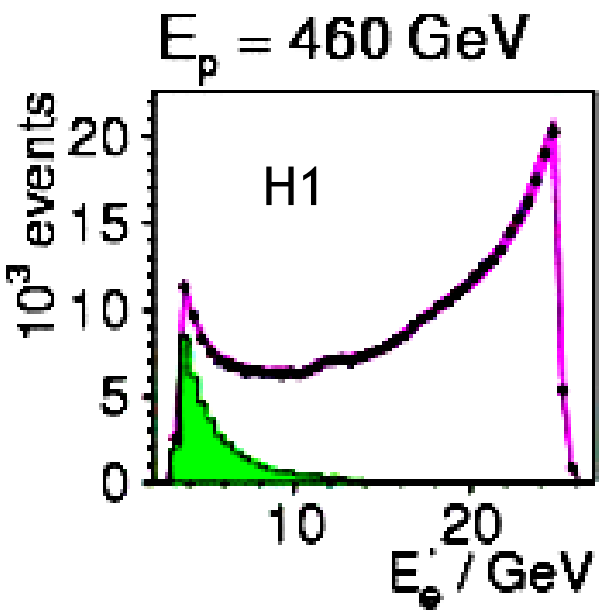

Still some differences to investigate, but HERA fit in agreement with either CTEQ or MSTW in all regions.

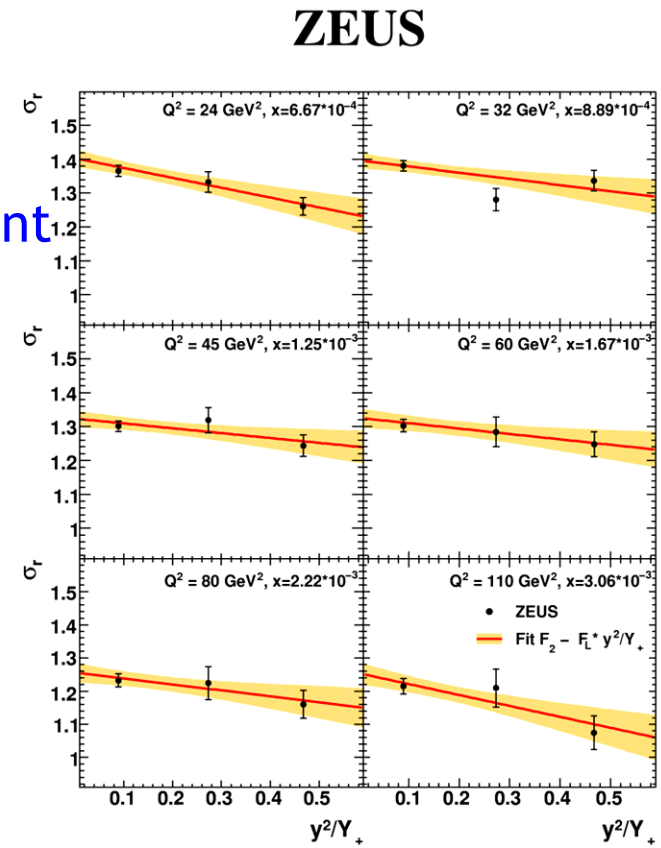
# Measurement of $F_L$

$$\sigma_r(x,Q^2,y) = F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2)$$

Need to measure the cross section at different beam energies ($E_P$=460, 575, 920 GeV)

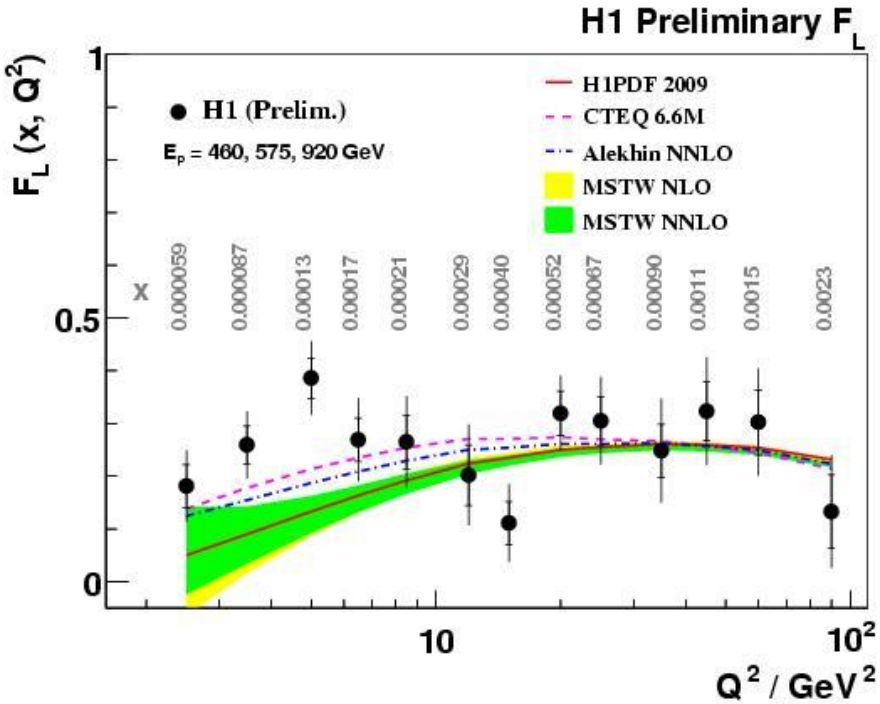
FL contribution only significant at high y
⇒ need to go to low electron energy

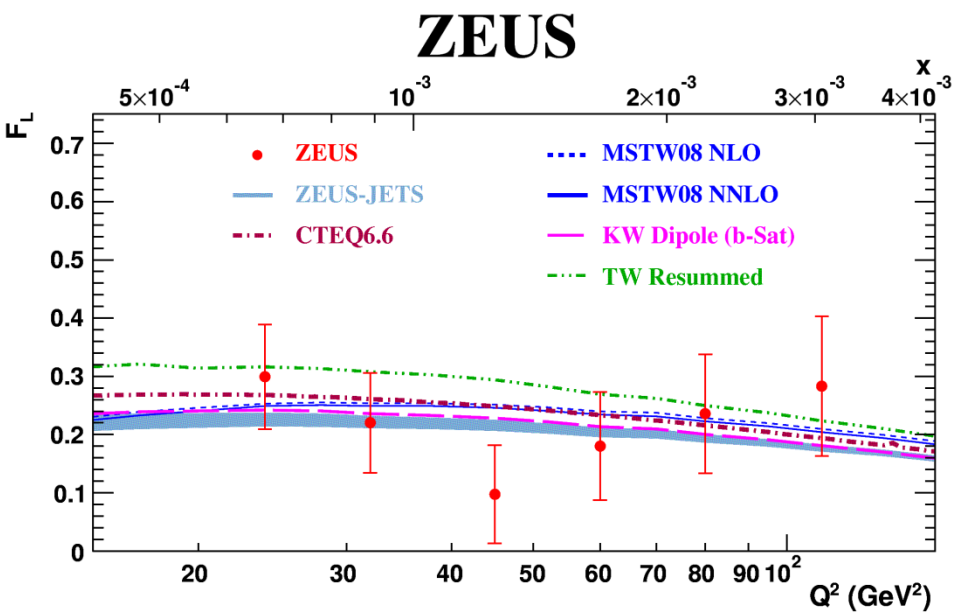



Fake electron background is large. Subtract with Monte Carlo (ZEUS) or with events with opposite electron charge (H1)

# Measurement of $F_L$




- Data at higher $Q^2$ agree well with QCD predictions
- At lower Q2 data tend to lie above H1 Fit and MSTW
- CTEQ and Alekhin describe data better

# Summary

•HERA has produced a wealth of inclusive NC/CC cross section measurements

• Measurement precision is now at low as 1%

• Accuracy improved by combining H1+ZEUS

• Data described by NLO QCD down to Q2=2.5 $GeV^2$ GeV

• QCD fits to data provide the most precise PDFs yet obtained, crucial to understand LHC physics

• Structure function $F_L$ measured directly