



# Measurements of deep inelastic scattering at HERA

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On behalf of the H1 and ZEUS Collaborations

- Introduction : motivation, HERA and DIS
- High  $Q^2$ , electroweak physics
- Comparison to theory and extracted PDFs
- HERAPDFs at the LHC
- Discussion and summary



# Introduction



# Motivation—DIS at HERA

Probe the electroweak structure of the Standard Model :

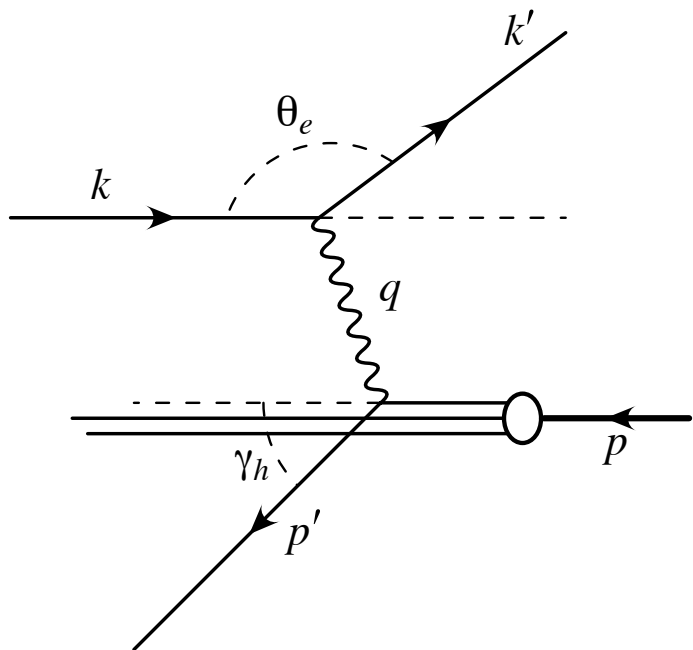
- Unification of electromagnetism and weak force.
- Chiral nature of electroweak force.

Want to understand the structure of the proton :

- As protons are bound by the strong force, can learn much on the (strong) interaction through study of the structure.
- Provide precise determination of the partonic density functions (PDFs) of the proton to be used at other proton colliders.

Comparison with theory may elucidate new physics, e.g. quark substructure, or will constrain it

# Deep inelastic scattering : definitions



Momentum transfer :

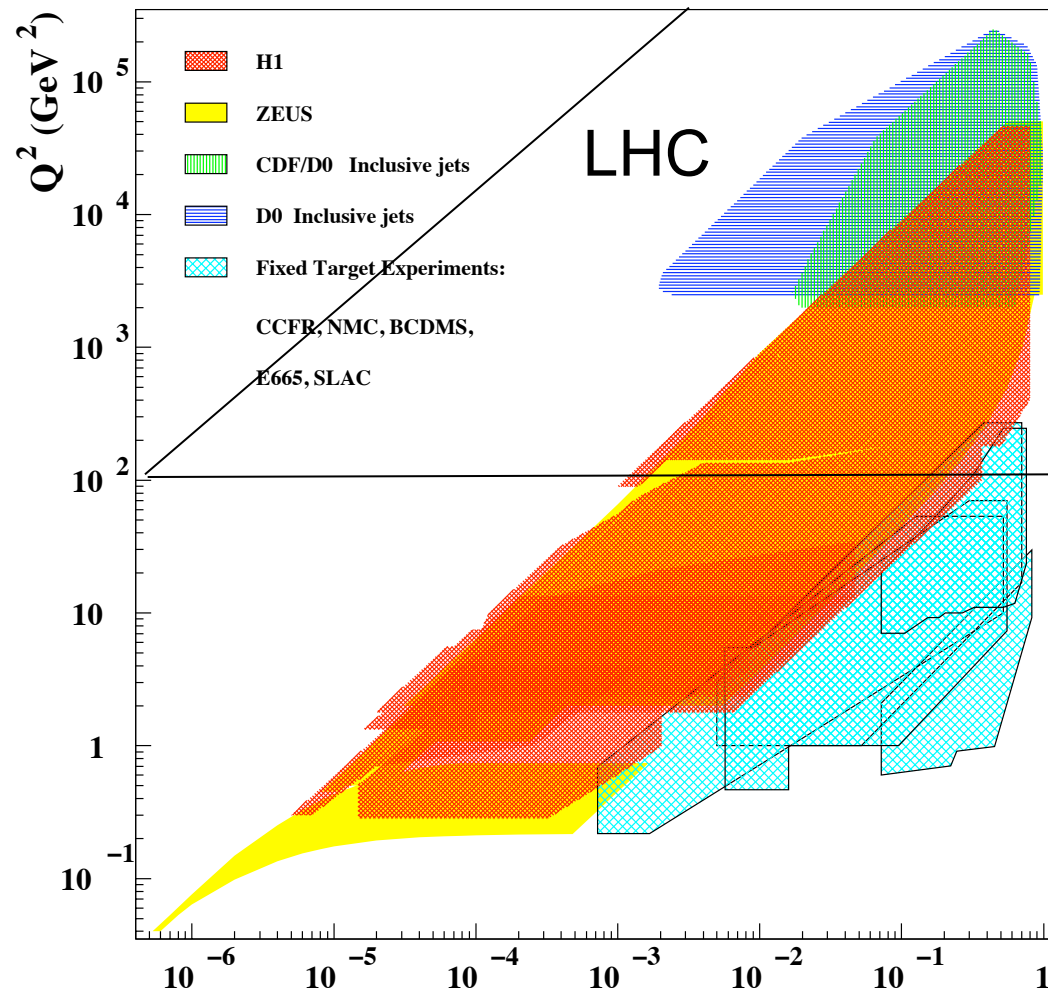
$$Q^2 = -q^2 = -(k-k')^2$$

Momentum fraction carried by struck parton :

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

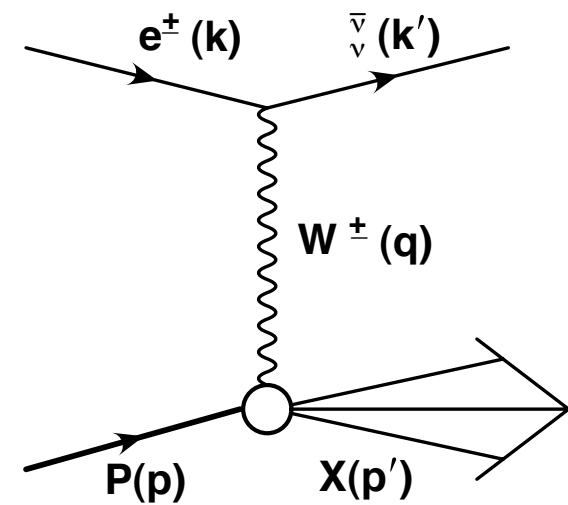
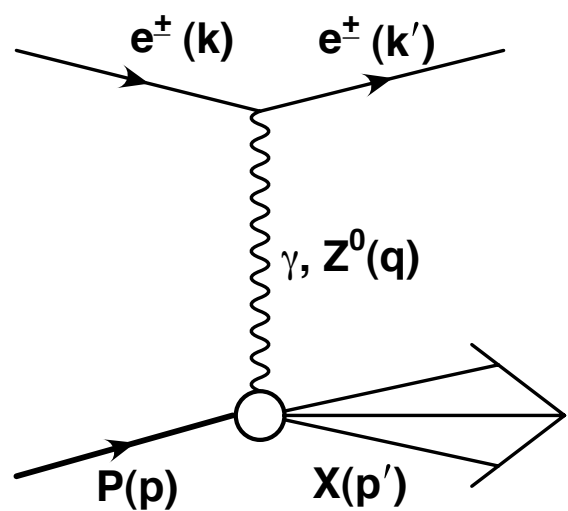
Inelasticity :

$$y = (q \cdot p)/(k \cdot p)$$



HERA overlaps with fixed-target, Tevatron and LHC experiments

# Neutral and charged current DIS processes



$$\frac{d^2\sigma^{e^\pm P}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} [Y_+ F_2 \mp Y_- xF_3 - y^2 F_L]$$

$$\frac{d^2\sigma^{e^\pm P}}{dx dQ^2} = \frac{G_F^2}{2\pi} \frac{M_W^2}{Q^2 + M_W^2} \tilde{\sigma}^{e^\pm P}$$

$F_2 \sim$  sum of  $q$  and  $\bar{q}$  densities

$$\tilde{\sigma}^{e^+P} \sim (\bar{u} + \bar{c} + (1-y)^2(d+s))$$

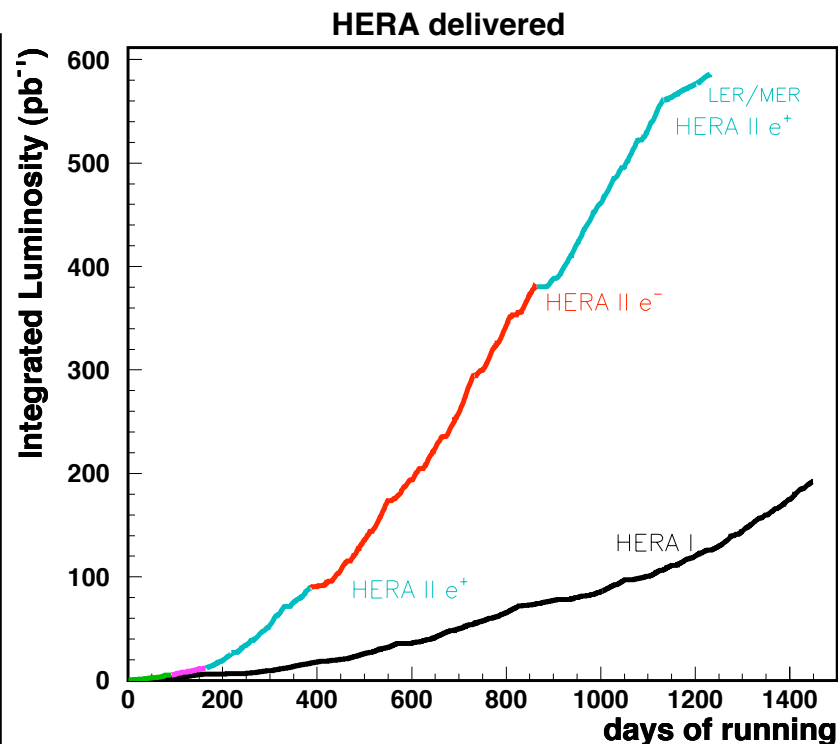
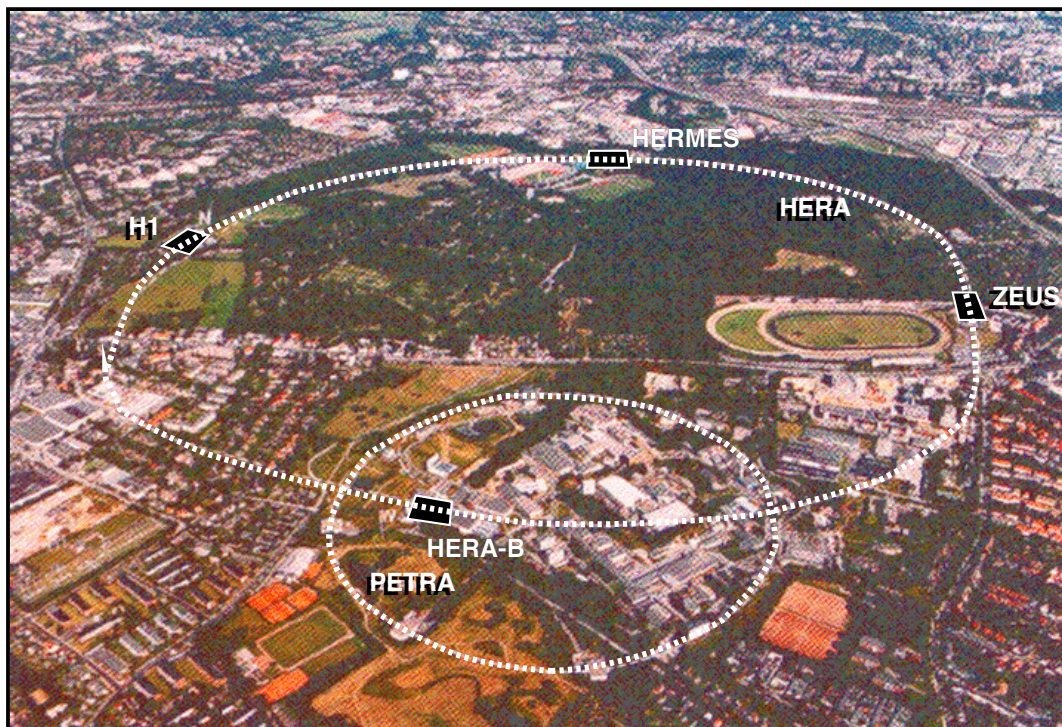
$xF_3 \sim$  density of valence quarks; from Z exchange

$$\tilde{\sigma}^{e^-P} \sim (u + c + (1-y)^2(\bar{d} + \bar{s}))$$

$F_L \sim$  gluon density

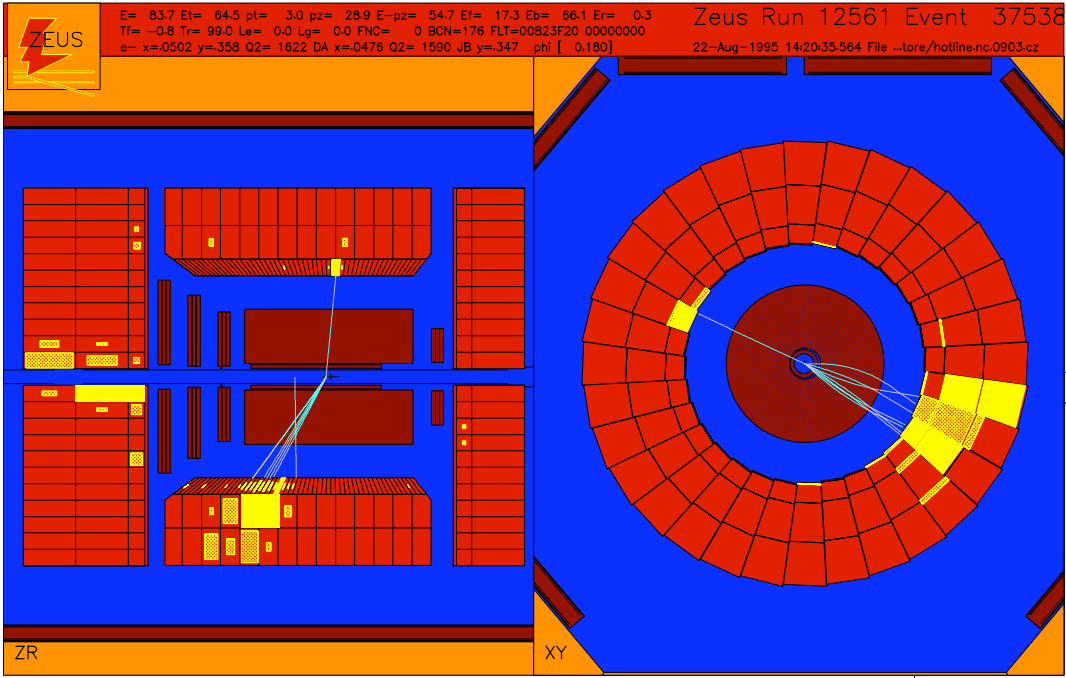
Sensitive to individual quark flavours

# The HERA collider



- During 1992–2007, mainly  $E_e = 27.5 \text{ GeV}$ ,  $E_p = 920 \text{ GeV}$  giving  $\sqrt{s} \sim 320 \text{ GeV}$ ; and dedicated data at different proton energies.
- Colliding-beam experiments collected combined sample  $\sim 1 \text{ fb}^{-1}$ .
- About 75% data taken with polarised ( $\sim 30\%$ ) lepton beams, with equal amounts of  $e^-$  and  $e^+$  and positive and negative polarisation.

# DIS events in H1 and ZEUS

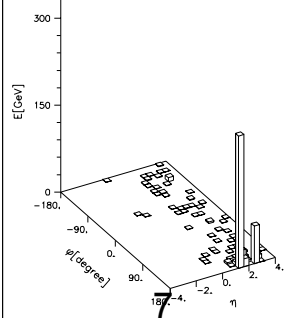
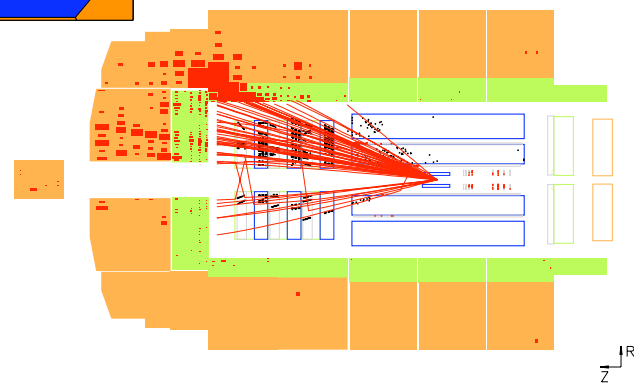
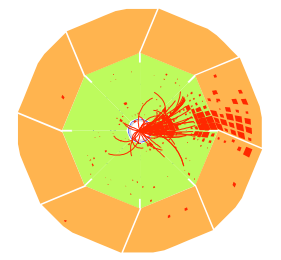


## Charge current :

- Missing  $p_T$  from escaped neutrino
- Hadronic jet
- Reconstruction not as precise, larger backgrounds

238837 Event 8595 Class: 4 5 6 7 11 19 25 26 28 run date 290399

9 Q2=41067 x=0.77 y=0.53

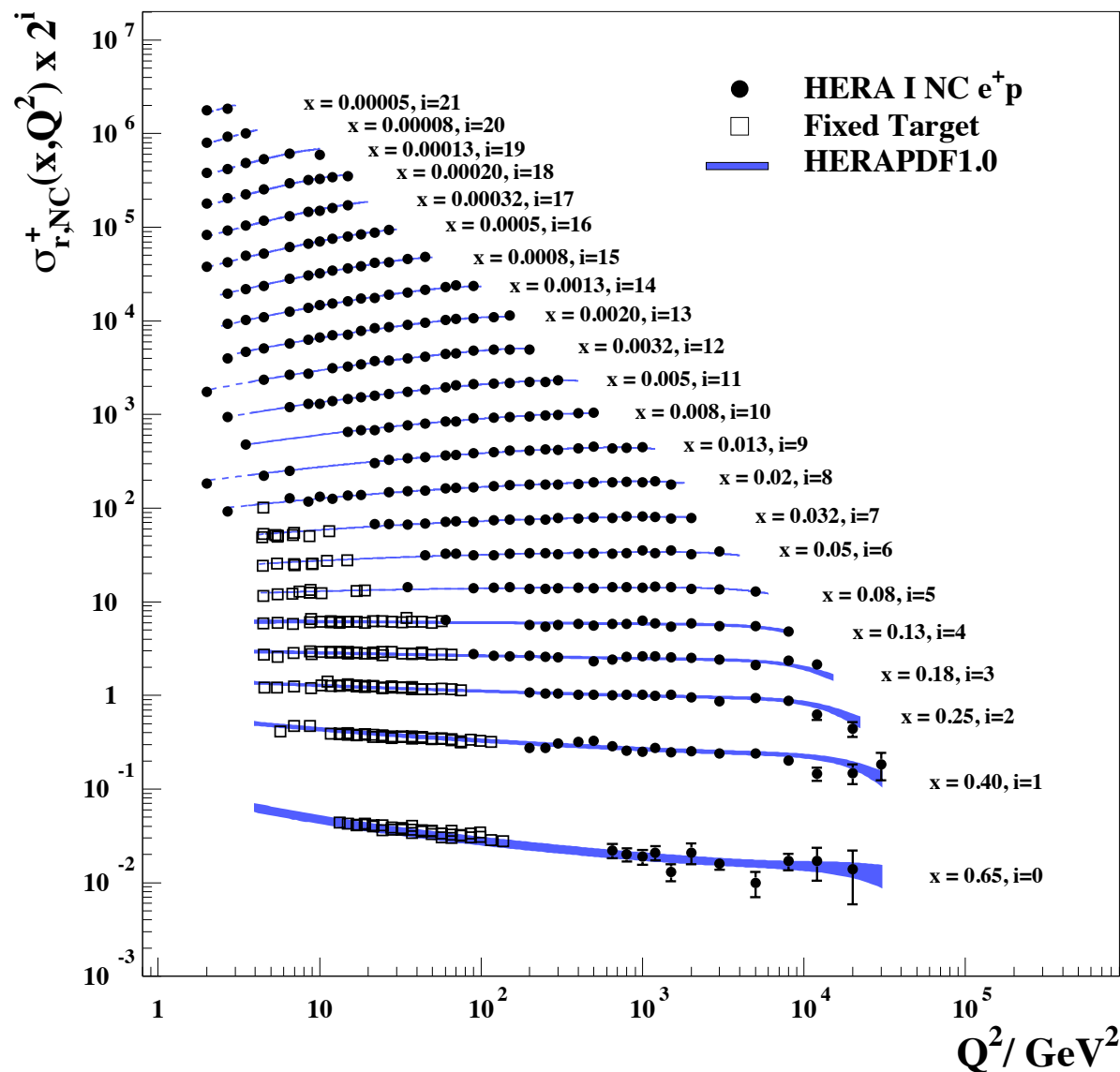


## Neutral current :

- High energy isolated electron
- Back-to-back with hadronic jet
- Kinematics can be reconstructed in several ways, clean samples

# Inclusive DIS data and HERAPDF fit

H1 and ZEUS



Impressive results for inclusive HERA I DIS data.



# New results, this talk

Results using HERA II data :

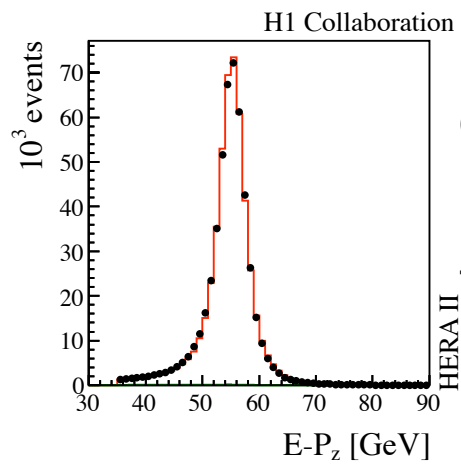
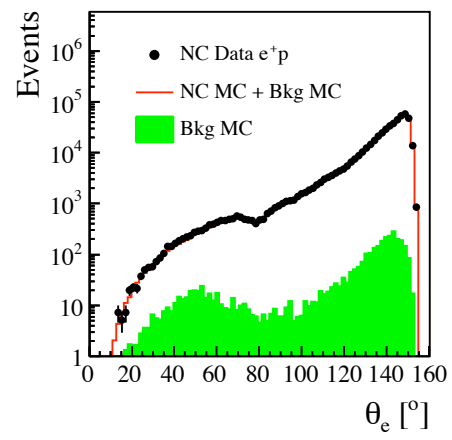
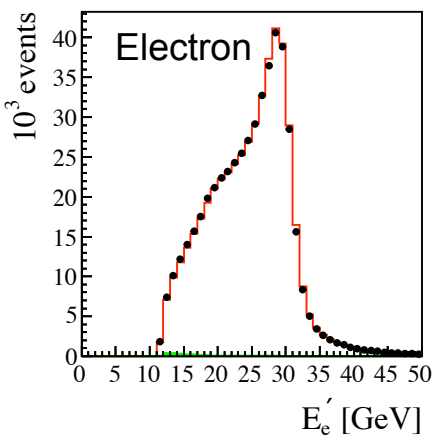
- More data
- Lepton polarisation
- More equal amounts of  $e^+$  and  $e^-$  data
- [ Lower energy proton running, charm, jet data ]

H1 Collaboration, “Inclusive deep inelastic scattering at High  $Q^2$  with longitudinally polarised lepton beams at HERA”, DESY-12-107, arXiv:1206.7007

ZEUS Collaboration, “Measurement of high- $Q^2$  neutral current deep inelastic  $e^+p$  scattering cross sections with a longitudinally polarised positron beam at HERA”, DESY-12-145, arXiv:1208.6138

ZEUS Collaboration, “Measurement of high- $Q^2$  charged current deep inelastic scattering cross sections with a longitudinally polarised positron beam at HERA”, Euro. Phys. J. **C70** (2010) 945

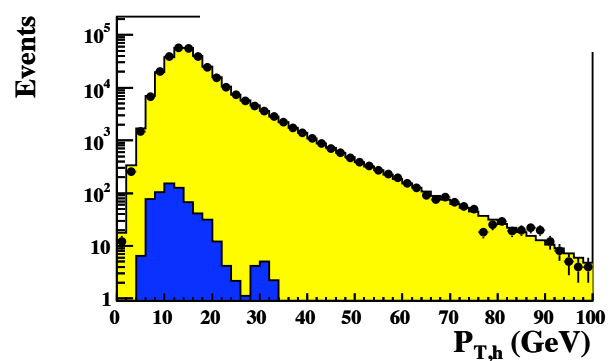
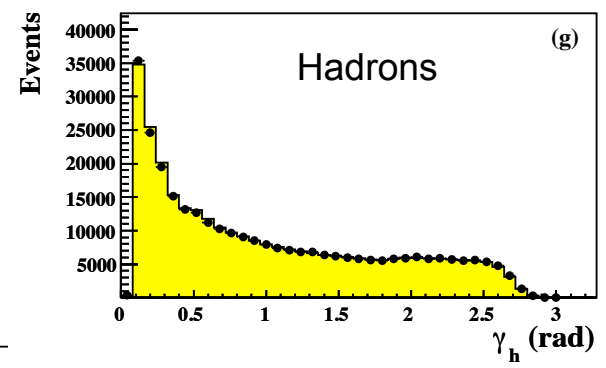
# Description of neutral current data



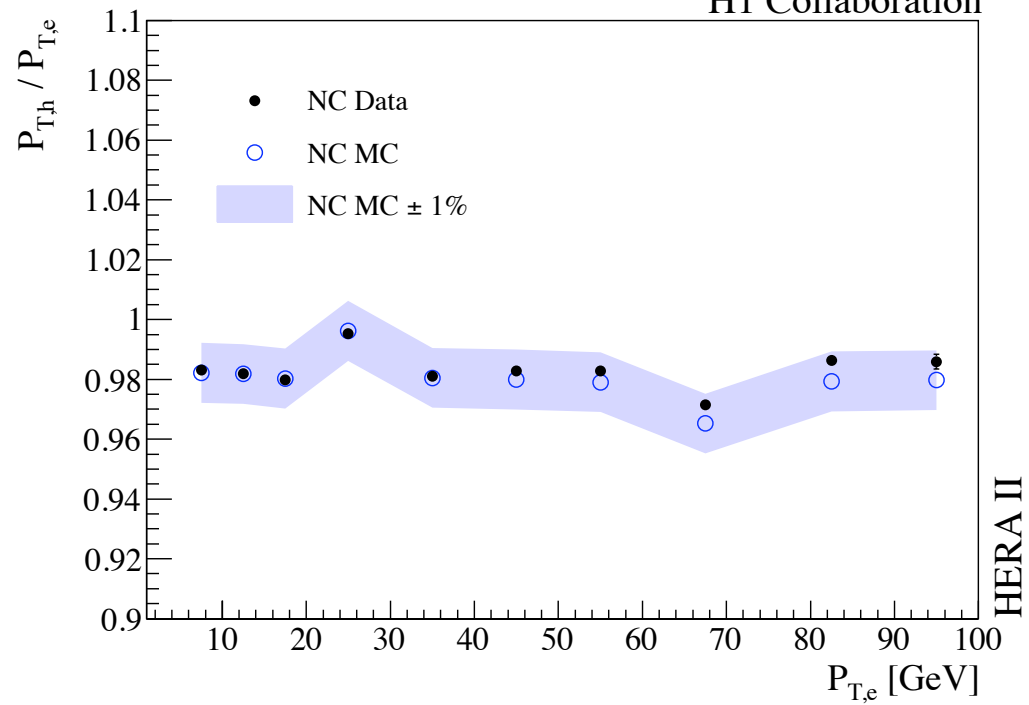
Need to understand electron (and hadrons) reconstruction.

Total uncertainty  $\sim 1.5\%$

ZEUS

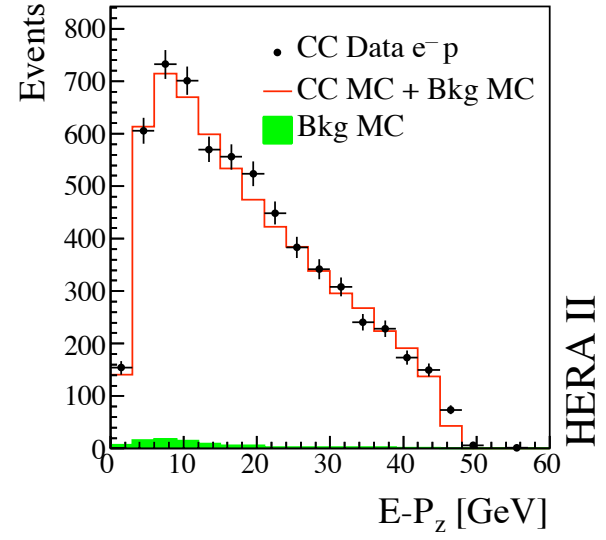
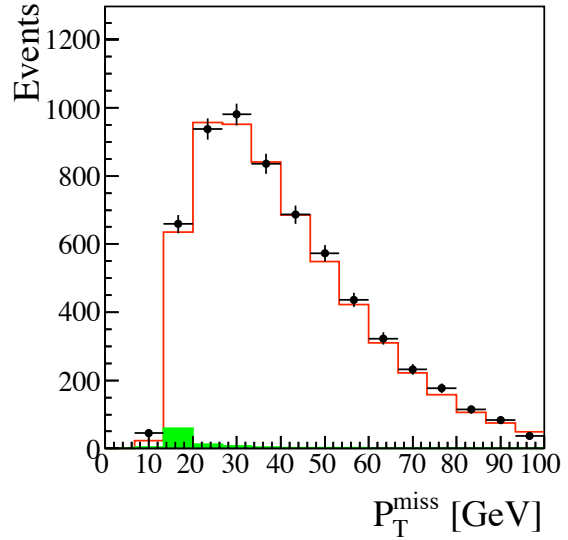


H1 Collaboration



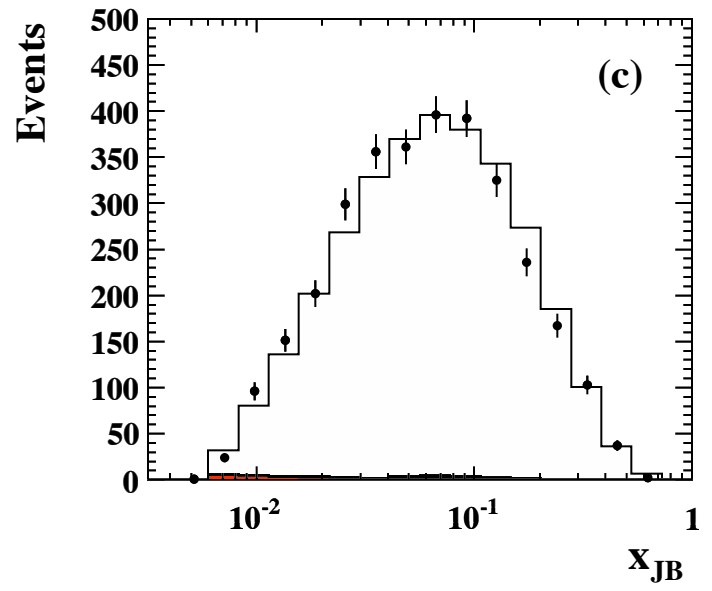
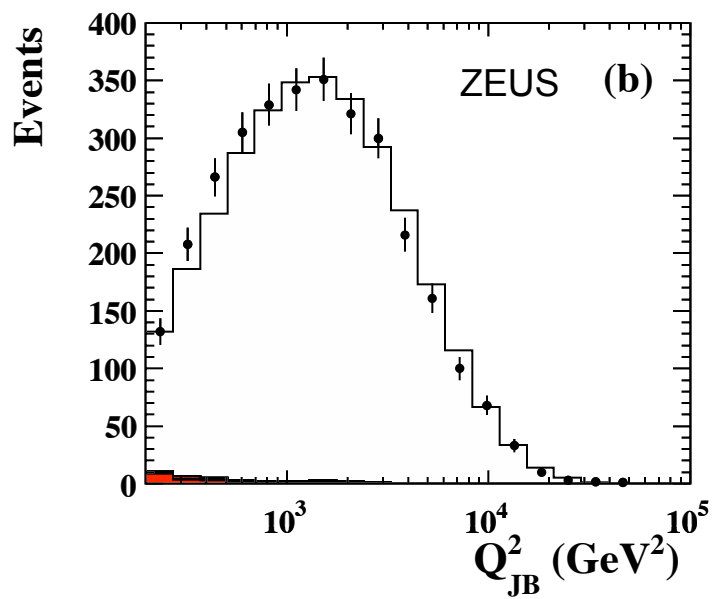
# Description of charge current data

H1 Collaboration



Need to understand missing energy and hadronic final state.

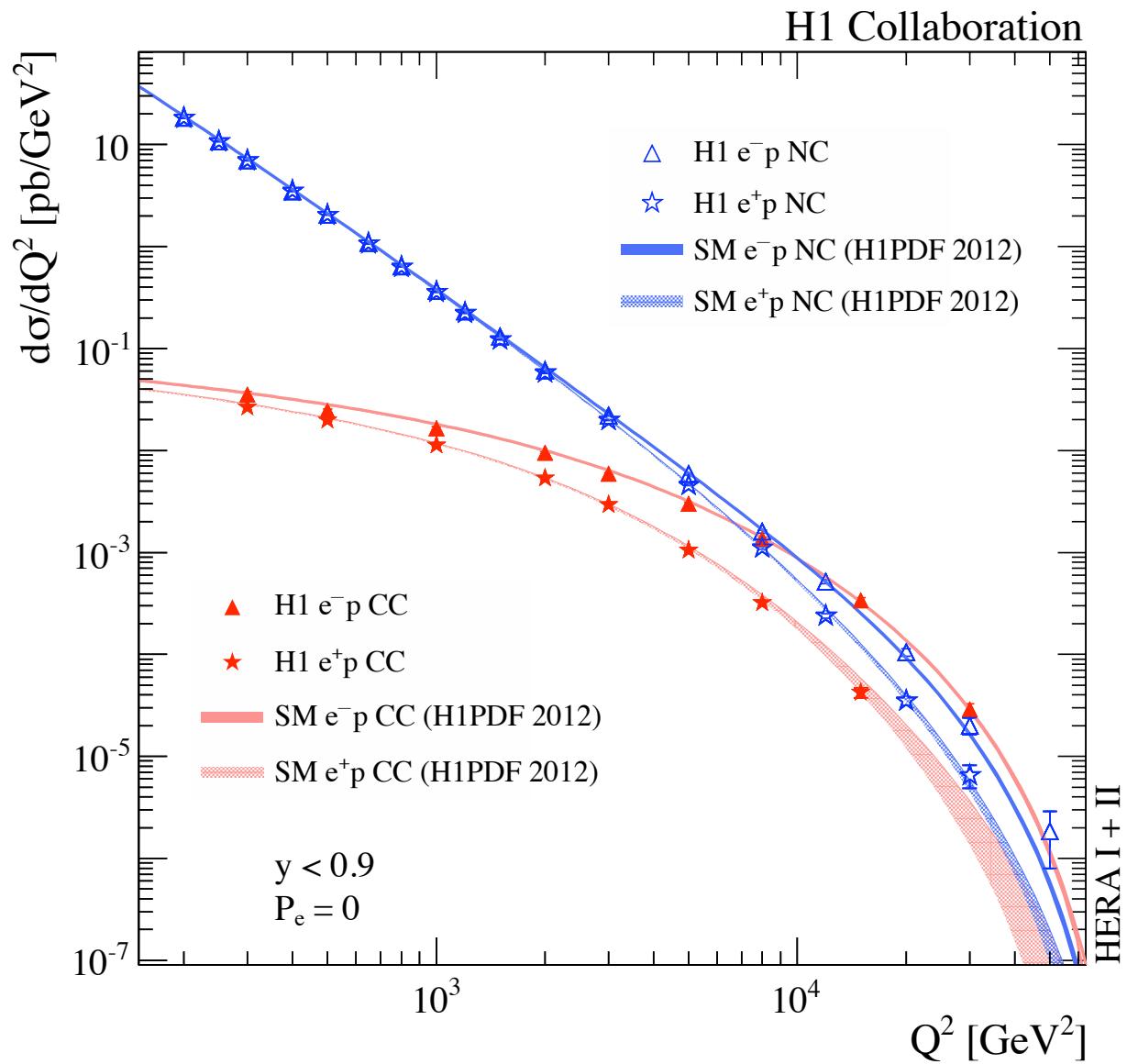
Total uncertainty  $\sim 3\%$





# High $Q^2$ , electroweak physics

# Electroweak unification





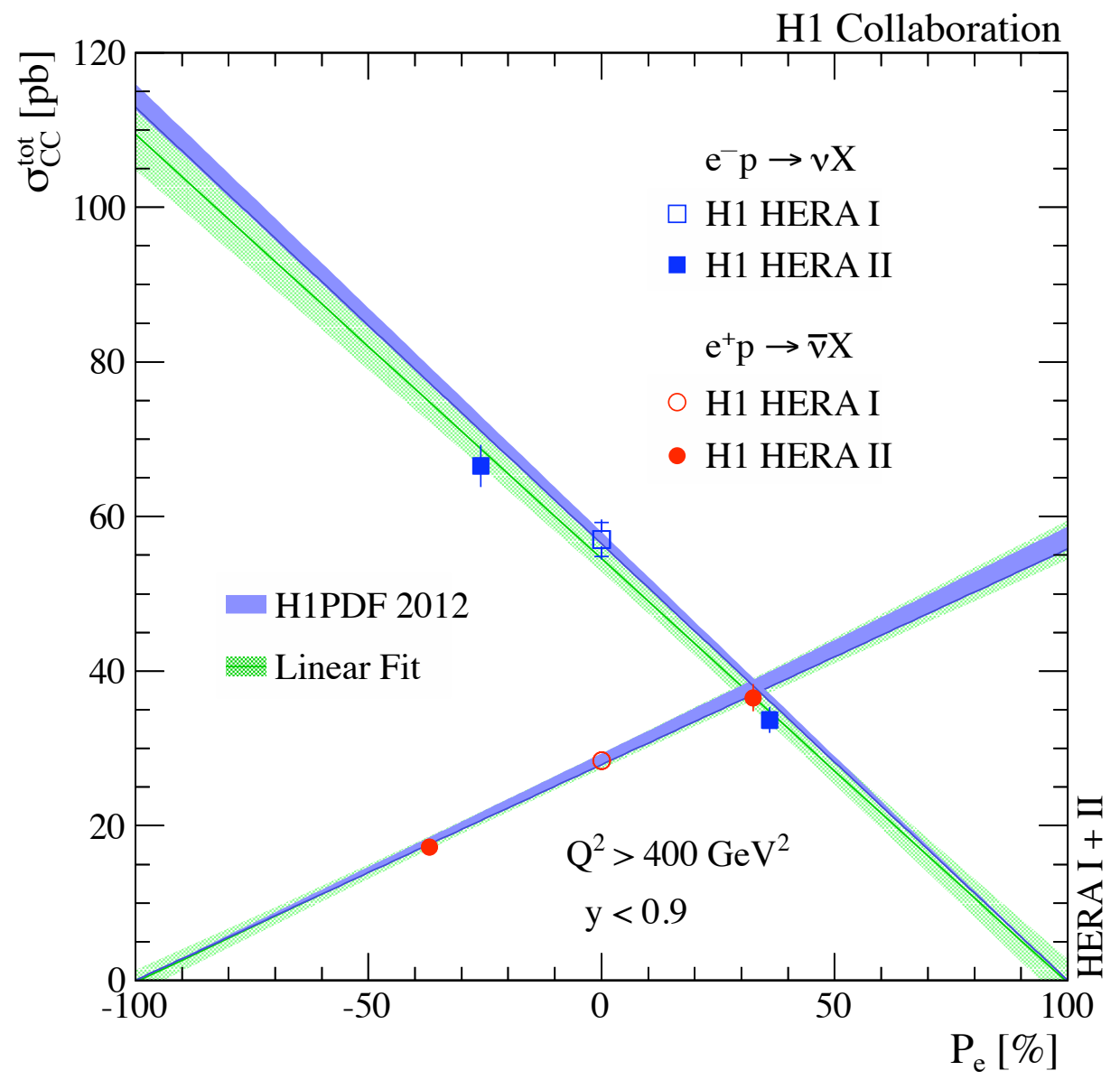
# Parity violation in charge current DIS

Probing chiral structure of electroweak interactions

Strong dependence of CC cross section on polarisation

Excellent description by theory

Rules out  $W_R$  bosons under 200 GeV





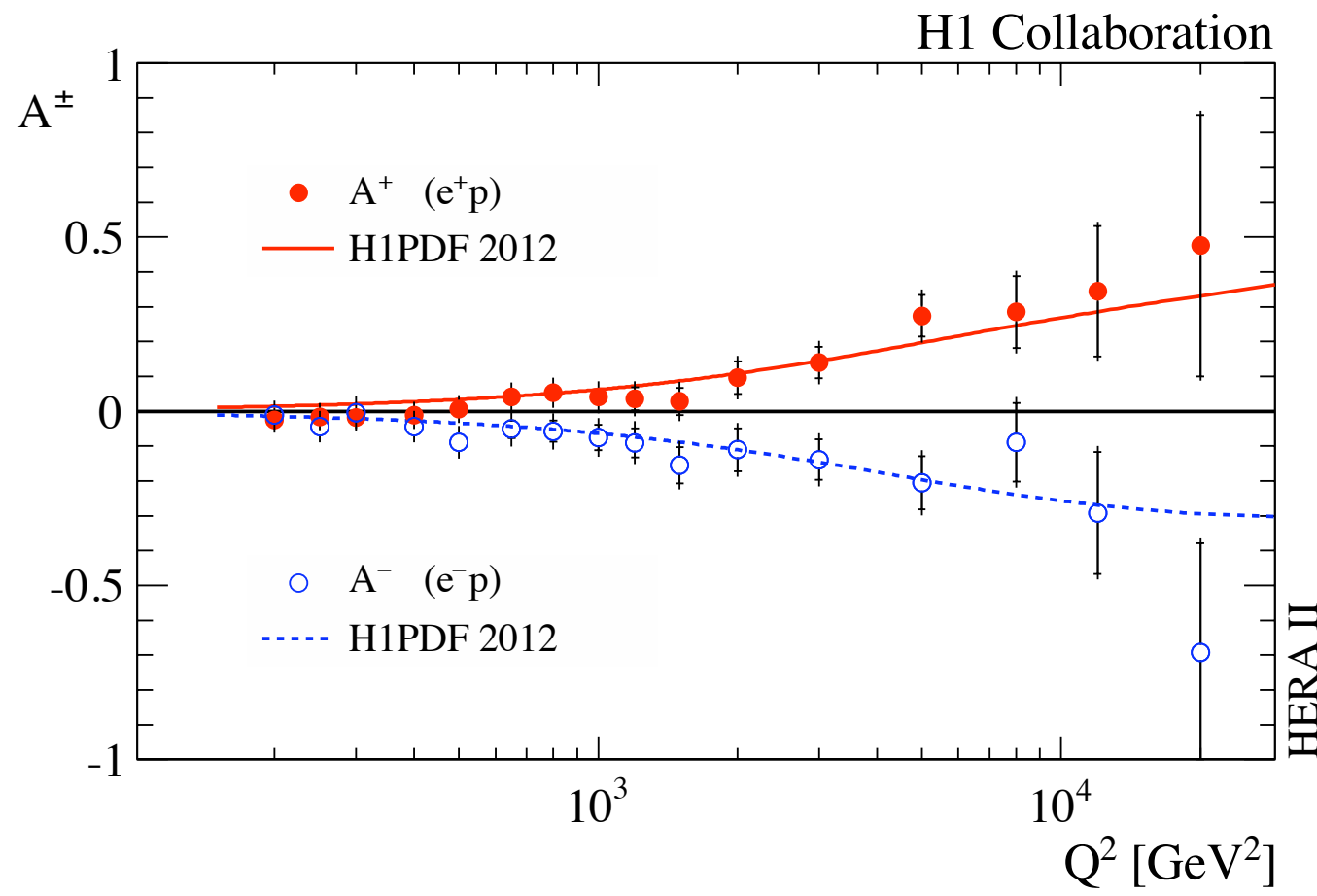
# Parity violation in neutral current DIS

Smaller, but still clear, dependence

Most clearly seen at high  $Q^2$

Confirms parity violation in electroweak interactions

$$A \sim a_e V_q$$

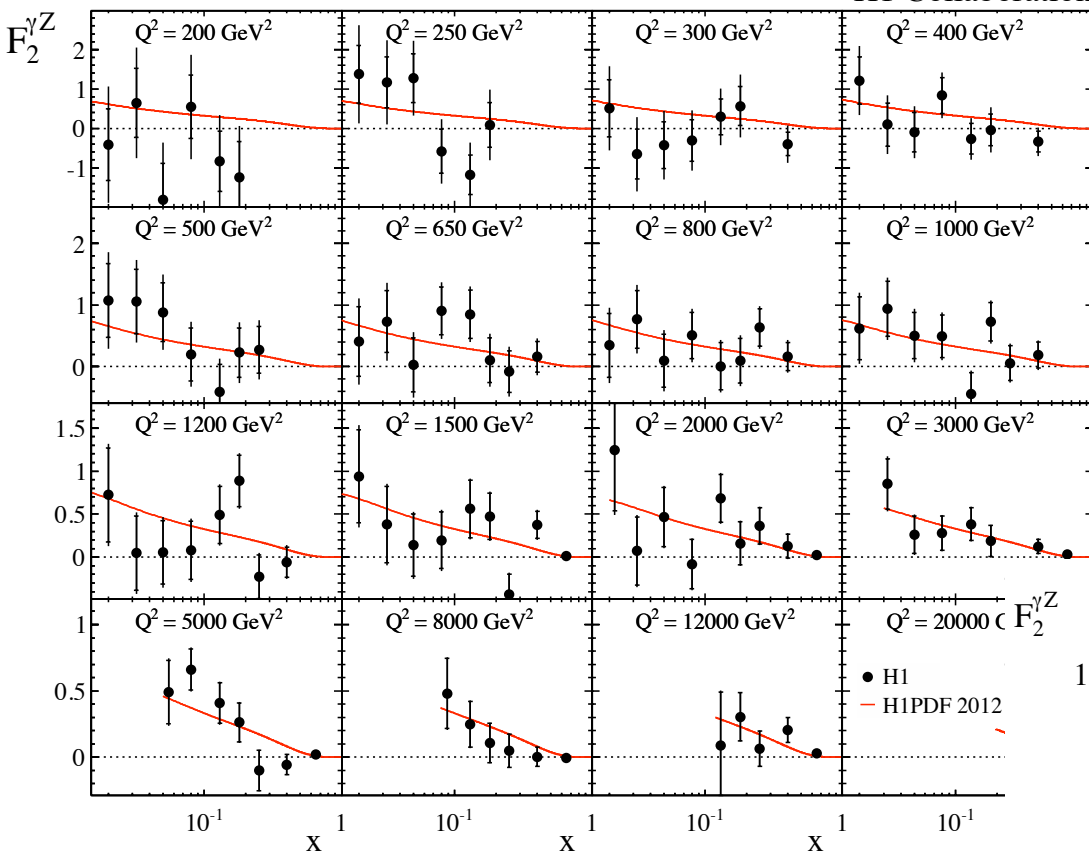


$$A^\pm = \frac{2}{P_L^\pm - P_R^\pm} \cdot \frac{\sigma^\pm(P_L^\pm) - \sigma^\pm(P_R^\pm)}{\sigma^\pm(P_L^\pm) + \sigma^\pm(P_R^\pm)} \quad 15$$



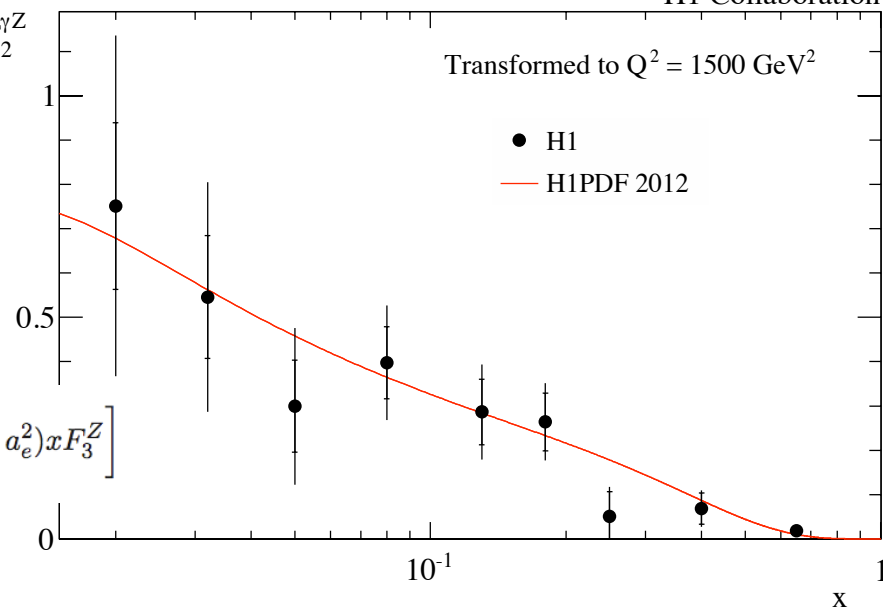
# Interference contribution to $F_2$

H1 Collaboration



First measurement of the neutral current parity violating structure function

H1 Collaboration



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

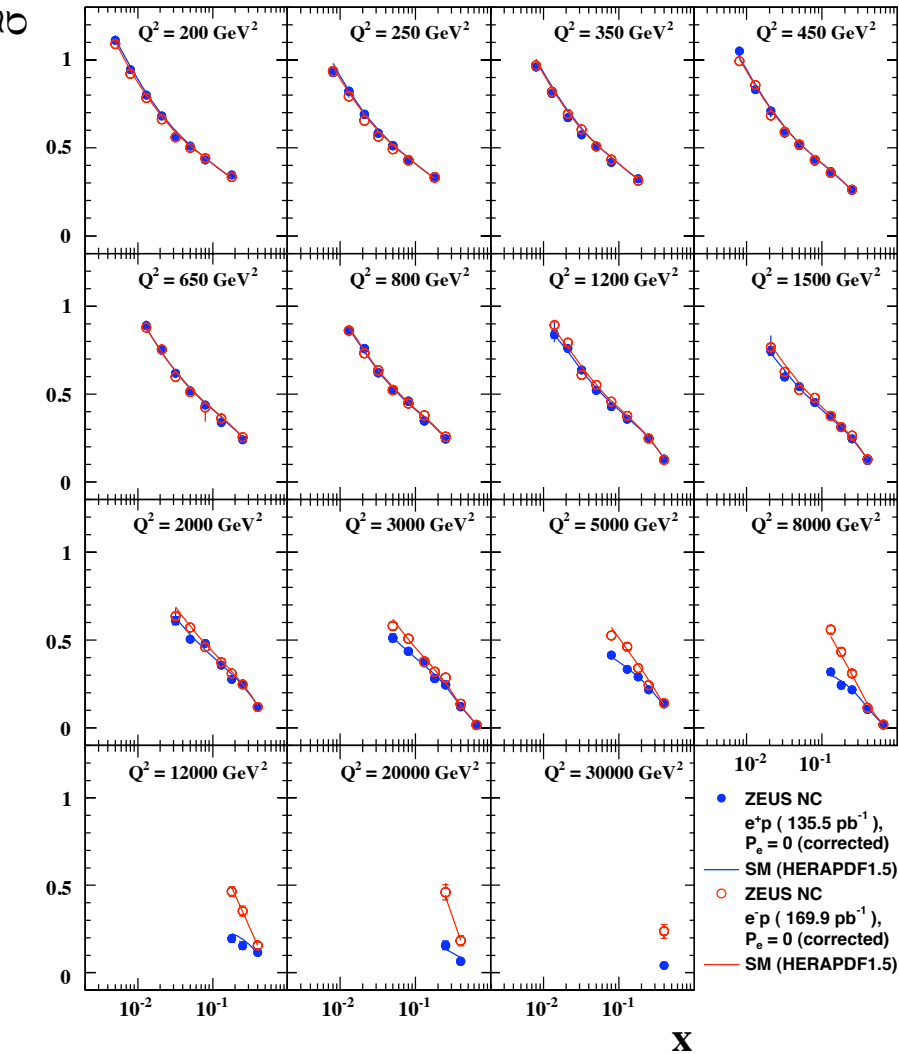




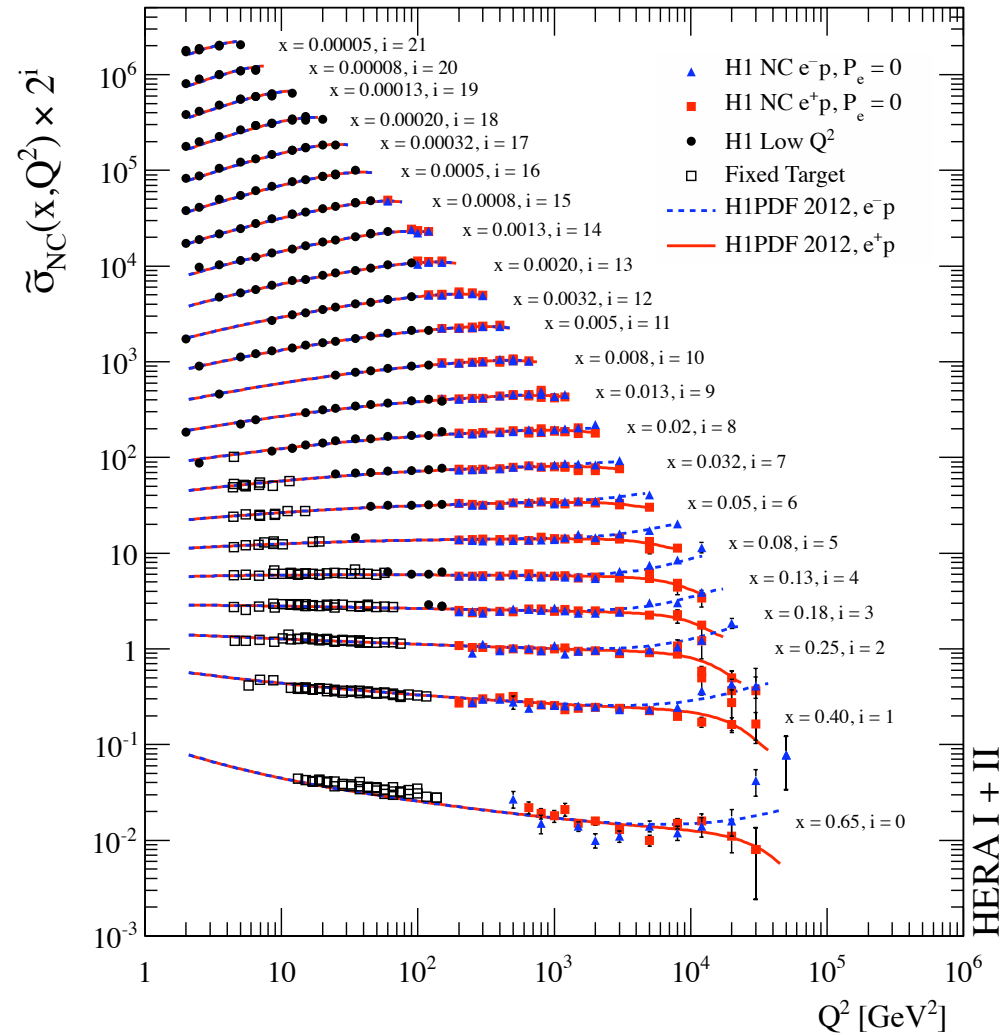
# Neutral current $e^+P$ and $e^-P$ data



## ZEUS



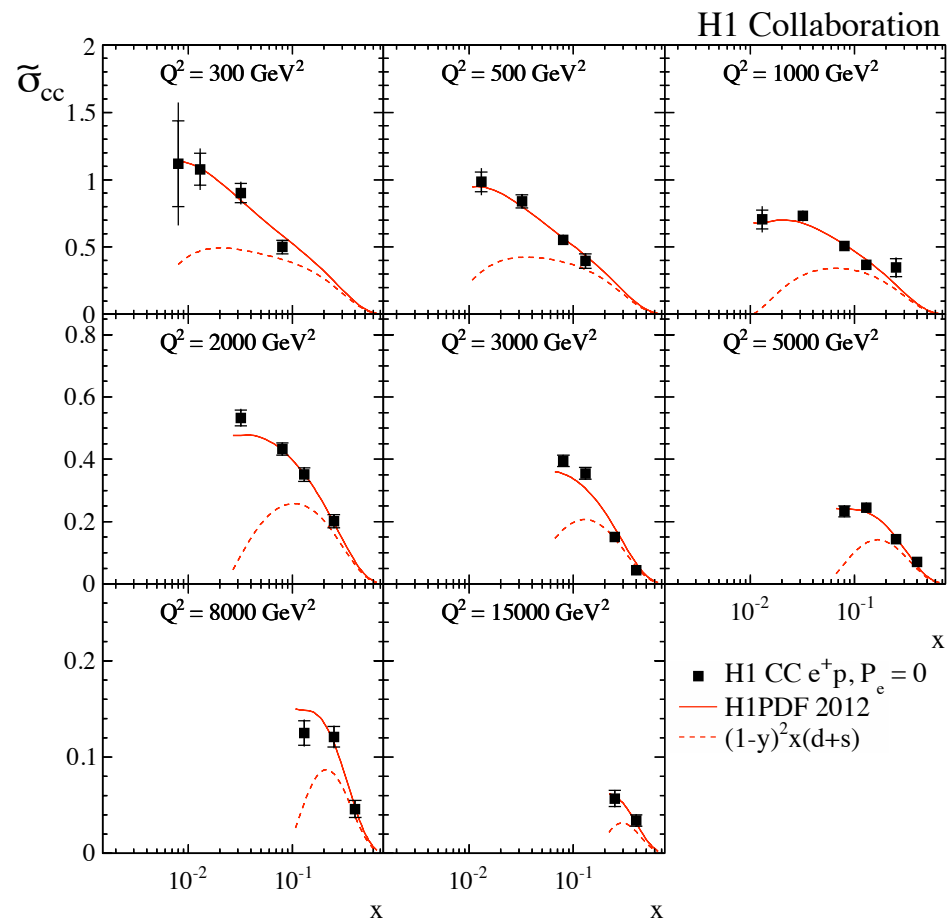
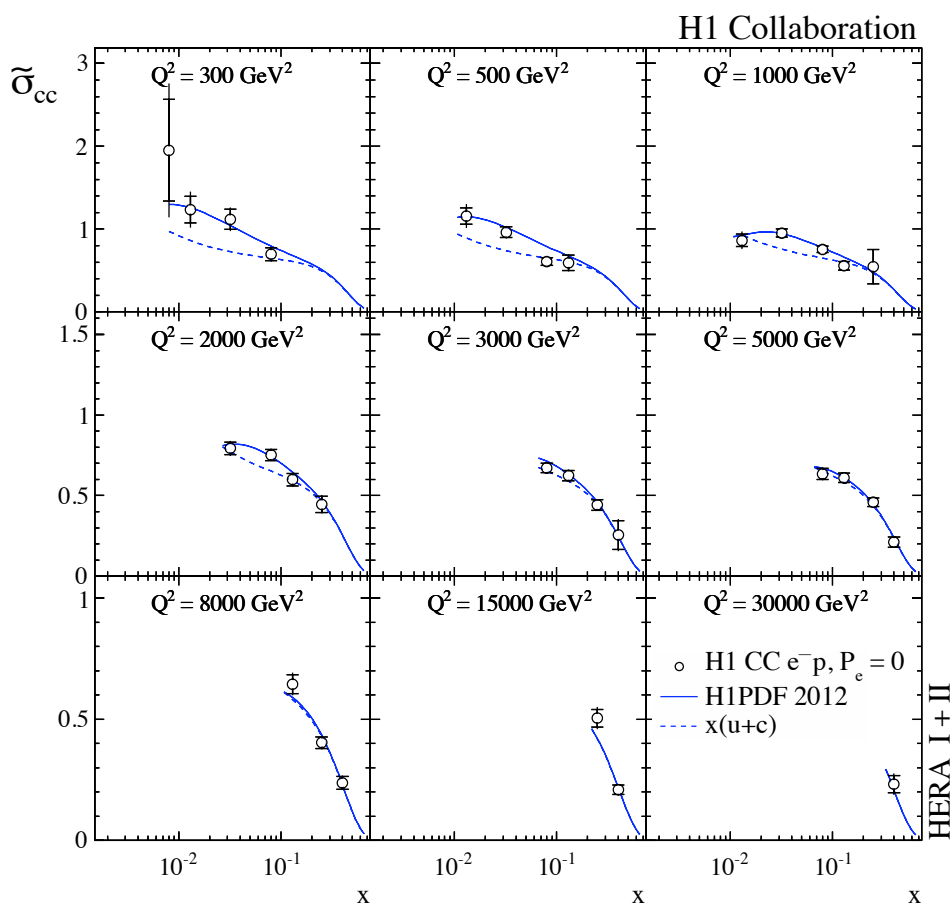
## H1 Collaboration



Difference in  $e^+P$  and  $e^-P$  data used to extract  $x F_3^{\gamma Z}$



# Charge current $e^+P$ and $e^-P$ data



The CC data can be used to separate the up- and down-type distributions in the proton

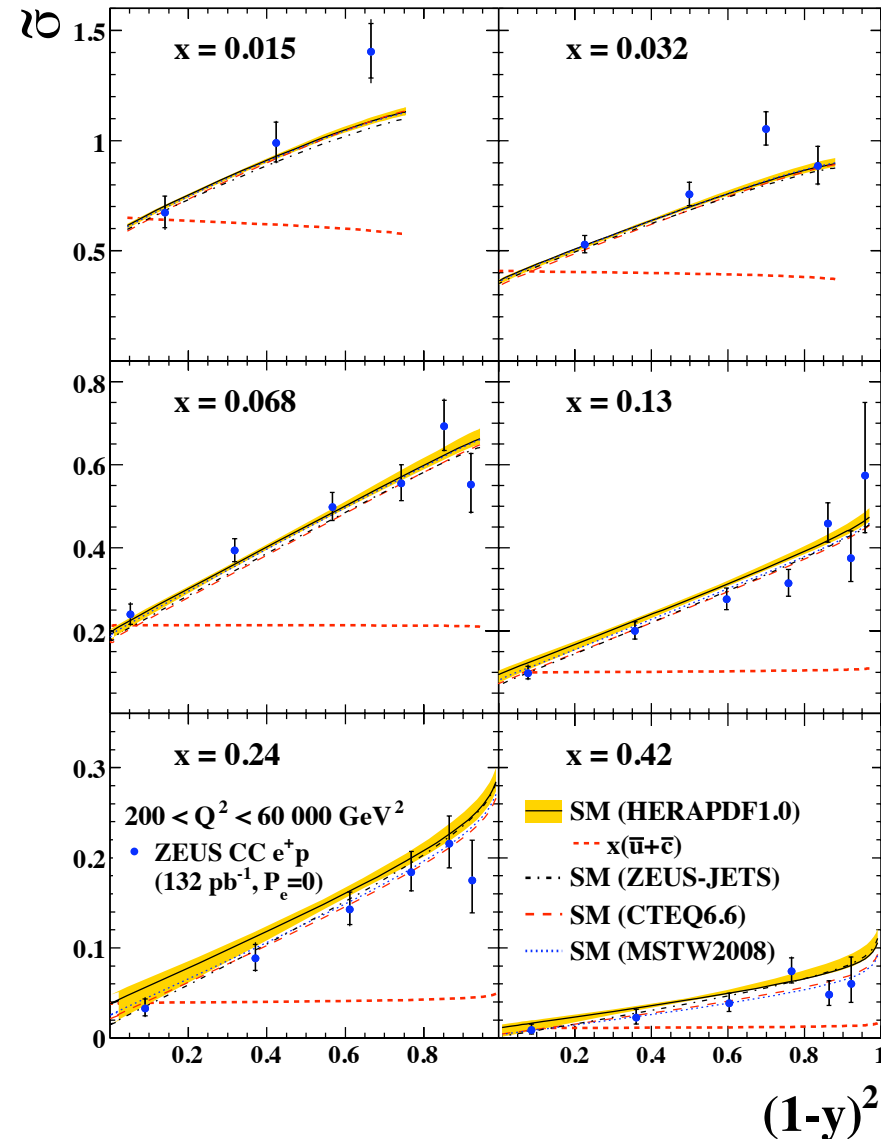
# Quark content in CC reactions

The  $W$  boson couples to left-handed fermions and right-handed anti-fermions

- Expect flat angular distribution for  $e^+q$  CC DIS
- Expect  $(1 + \cos\theta^*)^2$  in  $e^+q$  scattering

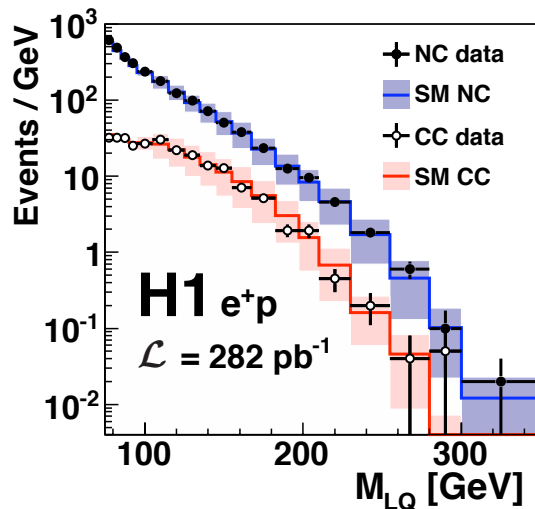
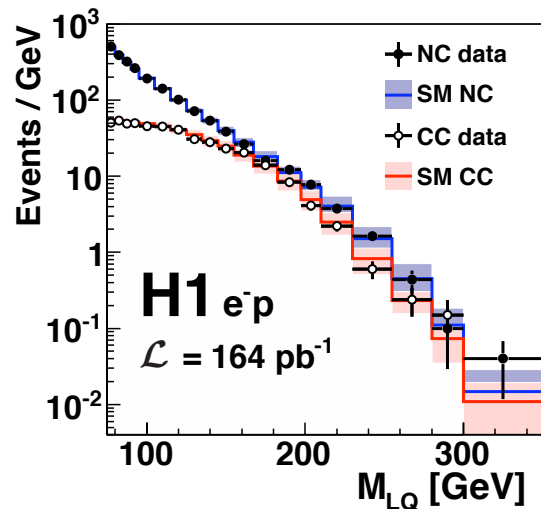
Intercept gives the  $(\bar{u} + \bar{c})$  contribution and the slope the  $(d + s)$  contribution

**ZEUS**



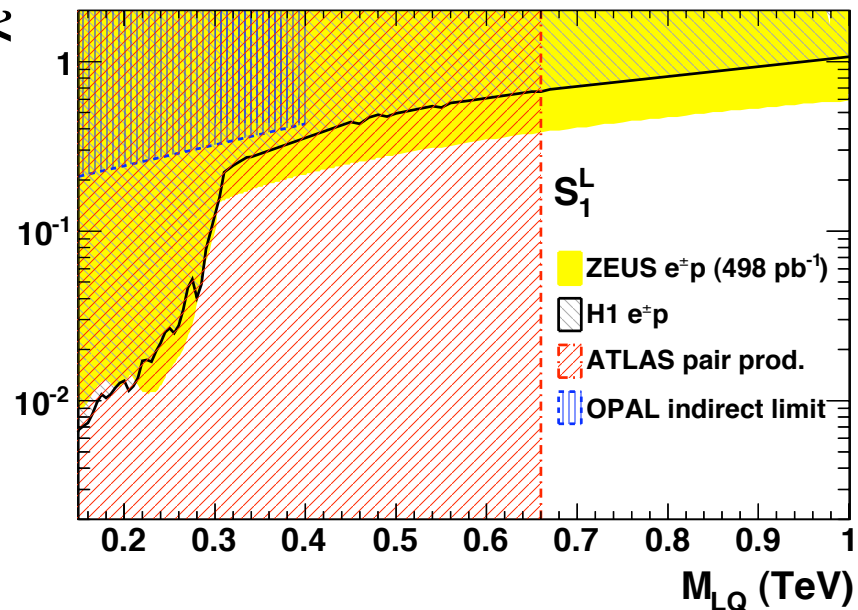
# Search / constraints for new physics

## H1 Search for First Generation Leptoquarks



High  $Q^2$  data can set limits on e.g. leptoquarks  $\lesssim$   
Allows contact-interaction analysis  
Constrain quark radius, extra dimensions, etc.

## ZEUS





# Comparison to theory and extracted PDFs

# Standard Model predictions

Discussion so far focused on electroweak effects and physics we can understand from general theory of the Standard Model

Now consider more detailed comparison with (combined electroweak and) QCD predictions and see what information can be extracted

Compare the data with the various fits of the parton distribution functions (PDFs) of the proton : CTEQ, MSTW, NN, HERA own

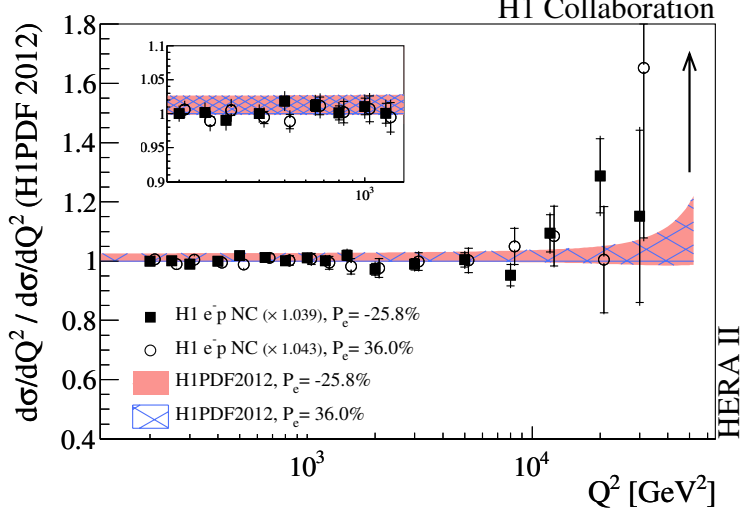
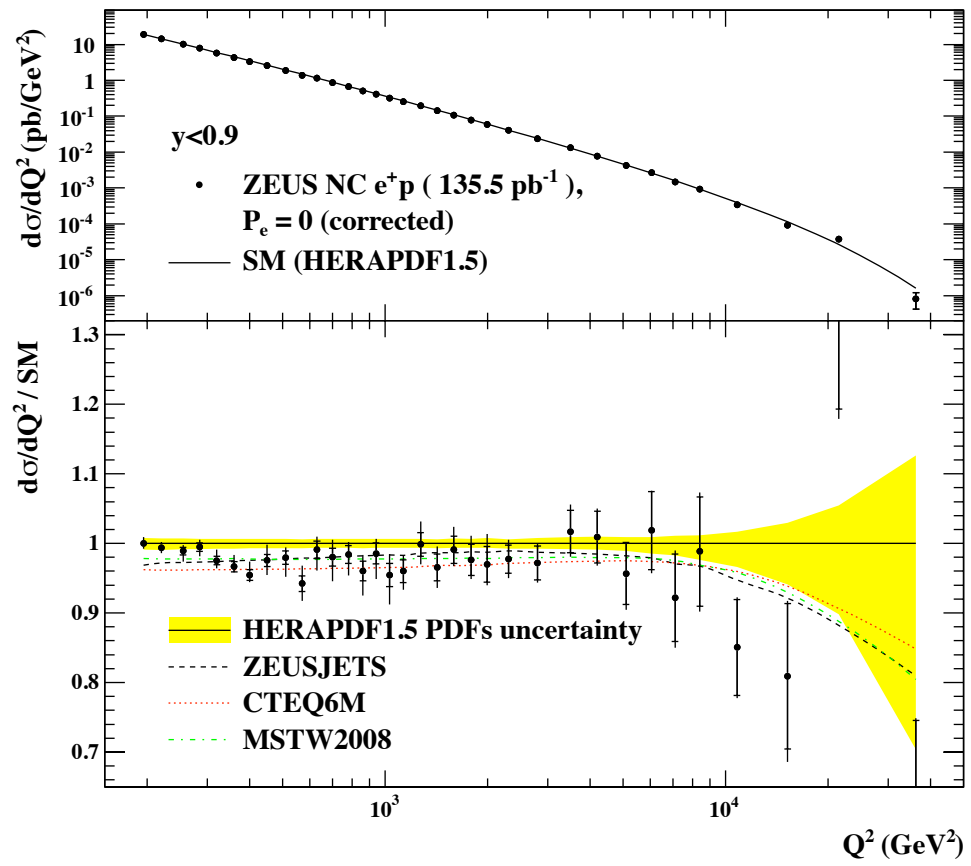
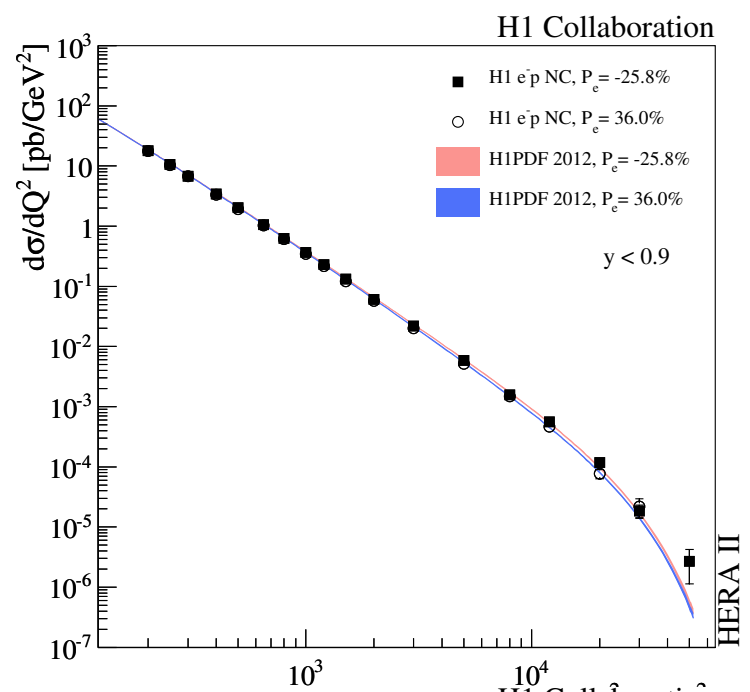
Use the data to further constrain the PDFs

[ Can also extract strong coupling,  $\alpha_s$  ]

The H1PDF, ZEUSPDF and HERAPDF are extracted using their own respective data with a complete understanding of the correlations of the errors

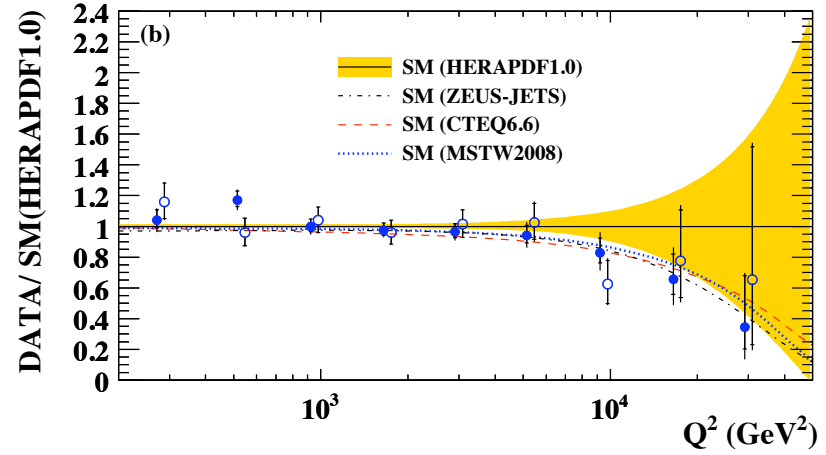
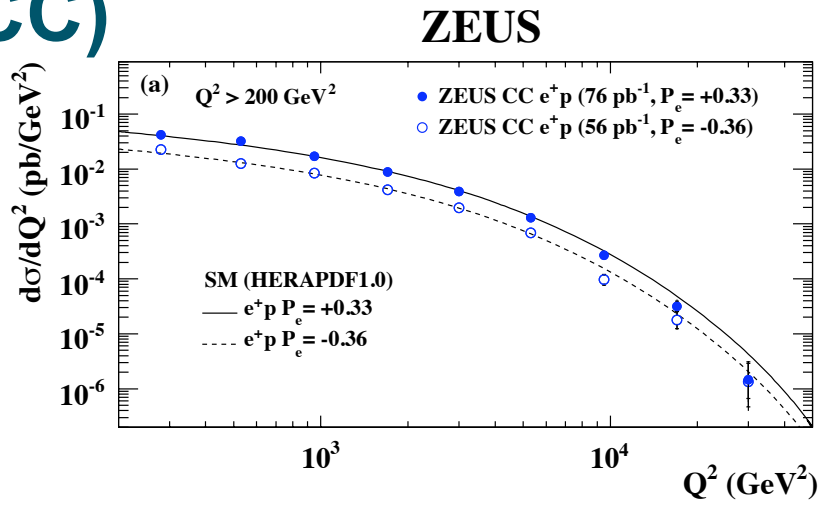
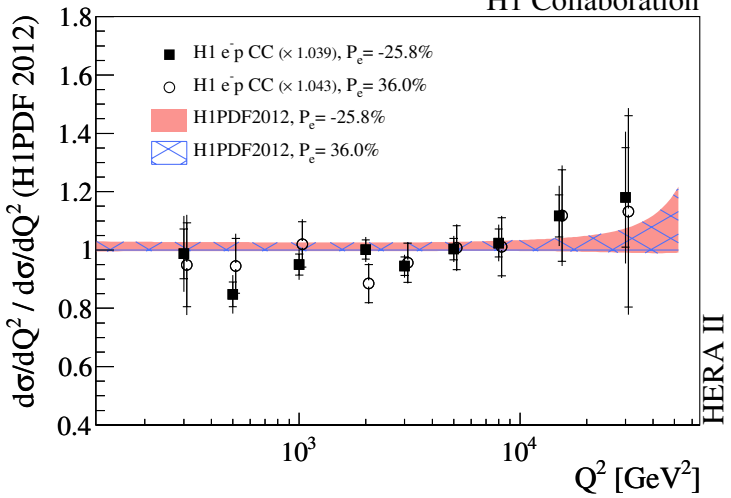
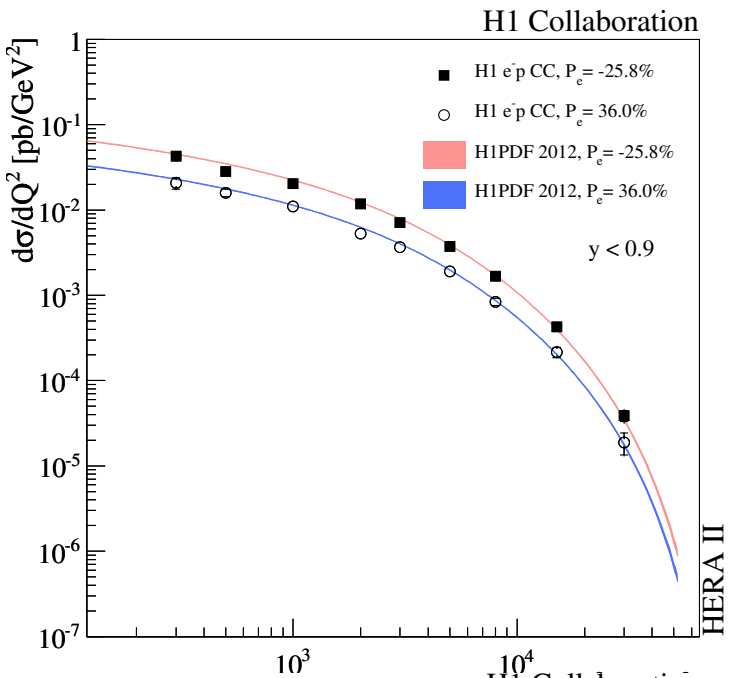
# Comparison to theory (NC)

ZEUS



Predictions of different PDFs all describe the data well

# Comparison to theory (CC)



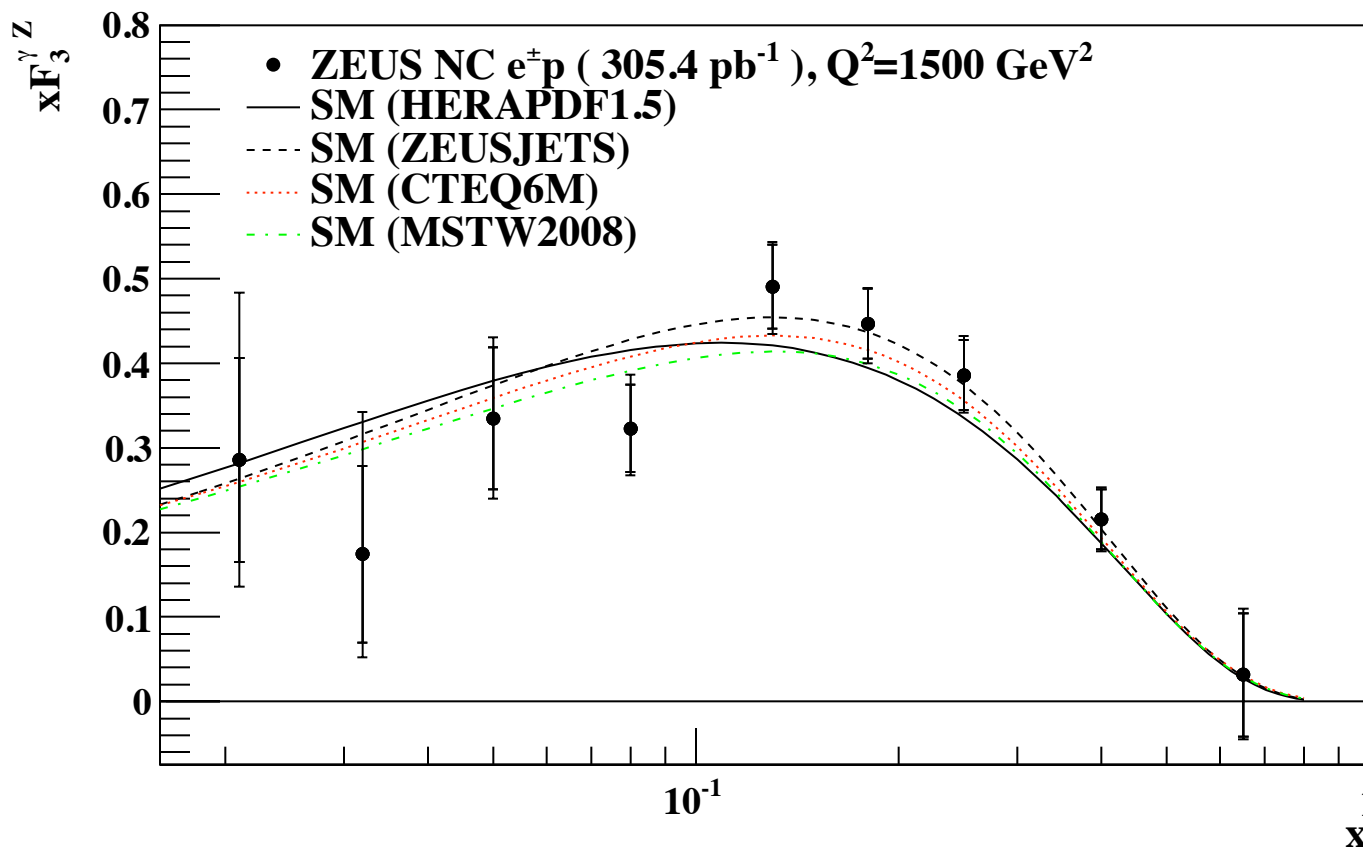
Ditto : predictions of different PDFs all describe the data well



# Comparison to theory III

Extracted from difference in  $e^+P$  and  $e^-P$  data and determines the valence distribution

## ZEUS



Again a good description by all PDFs

# Extraction of parton densities

$$\sigma_{DIS} \sim f_P \otimes \sigma_{pert}$$

$f_P$  : proton parton density function evolved with  $Q^2$  by DGLAP equations.

$\sigma_{pert}$  : short distance cross section calculable in pQCD.

- The structure of (parton densities in) the proton extracted from fits to DIS data.
- Use next-to-leading order (NLO) QCD, and now NNLO QCD, a series expansion in  $\alpha_s$  with e.g. hard scale  $Q^2$  and assumptions : heavy quark masses, the starting scale, the strong coupling, the functional form of the parton density functions, etc..

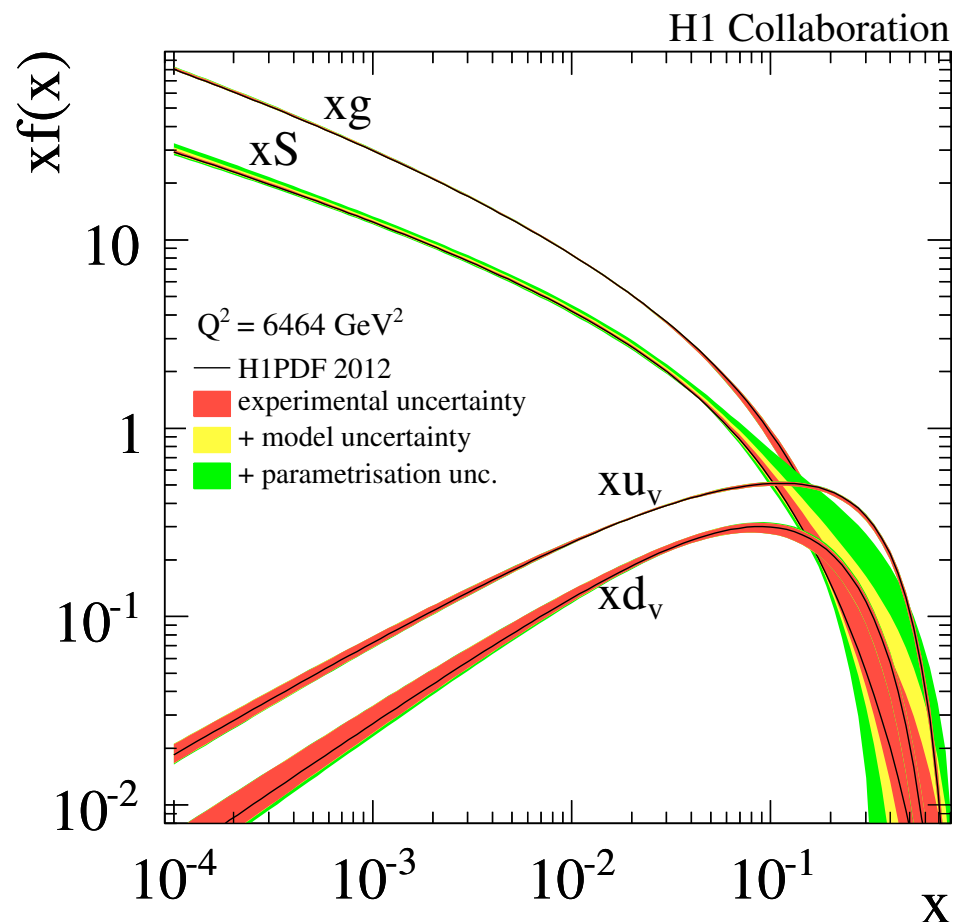
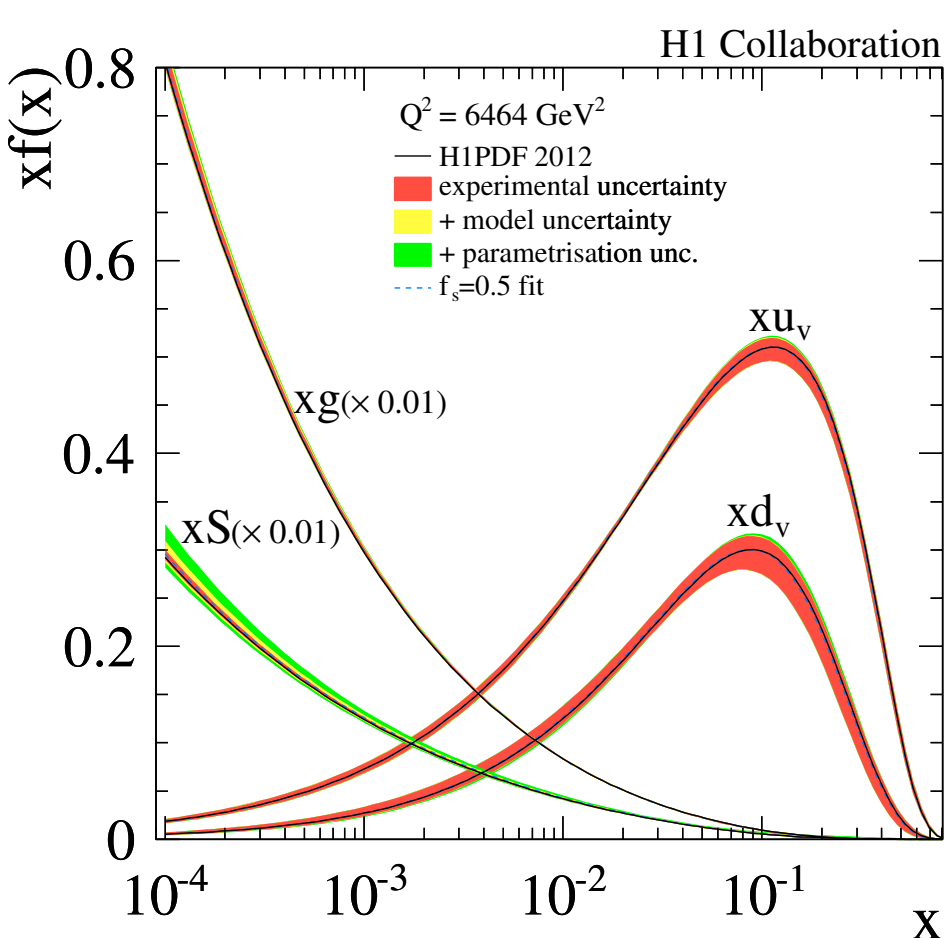
Data used :

- H1PDF2012, H1 HERA I + II inclusive DIS data
- Similar in spirit to HERAPDF fits

Uncertainties :

- Experimental—using  $\Delta\chi^2 = 1$
- Model—heavy quark masses, minimum  $Q^2$  and strange quark distribution
- Parameter—envelope of parameter variations.

# Extraction of PDFs



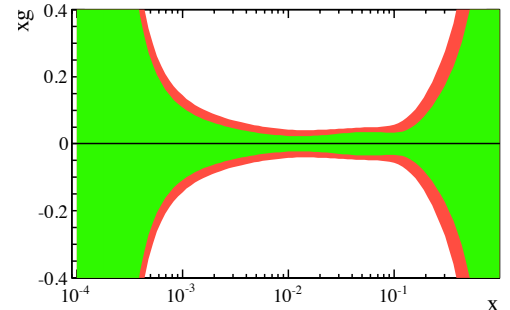
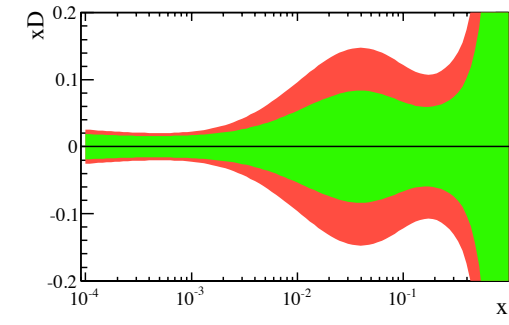
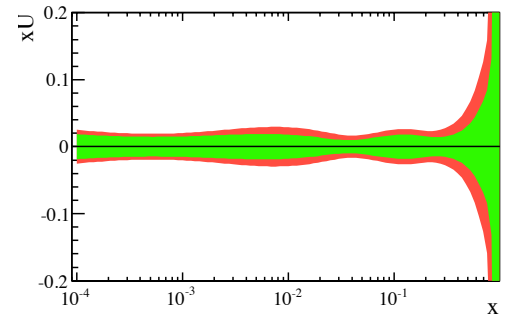
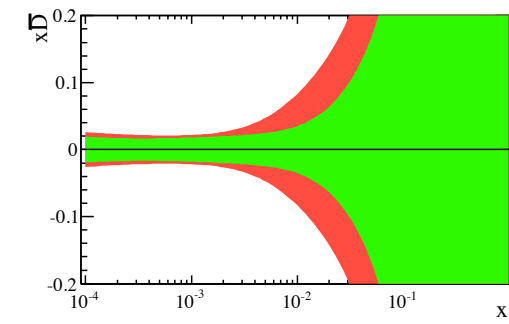
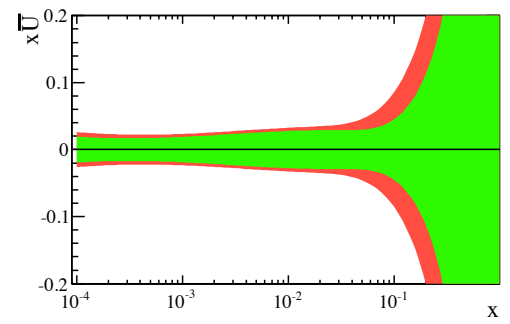
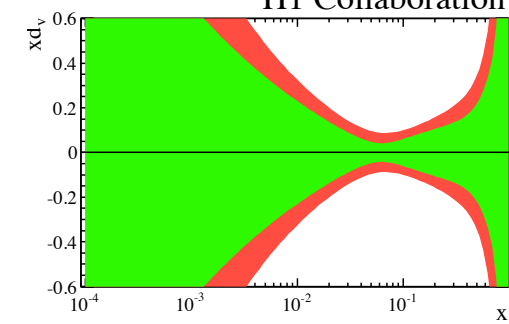
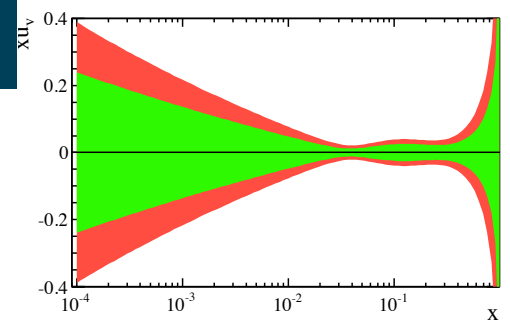
Good fit,  $\chi^2 / ndf \sim 1$ , for combined HERA I + II data, evaluated at  $M_W^2$



# Effect of HERA II data on PDFs

Redoing fit without HERA II data :

- Impact on all distributions
- Reduction by factor of up to 2 in uncertainties.
- Most significant in  $xD$  distribution
- Will feed into HERAPDF (and other global fits)



■ Uncert. due to H1 HERA I data  
■ Uncert. due to H1 HERA I+II data  
 $Q^2 = 1.9 \text{ GeV}^2$



# HERAPDFs at the LHC

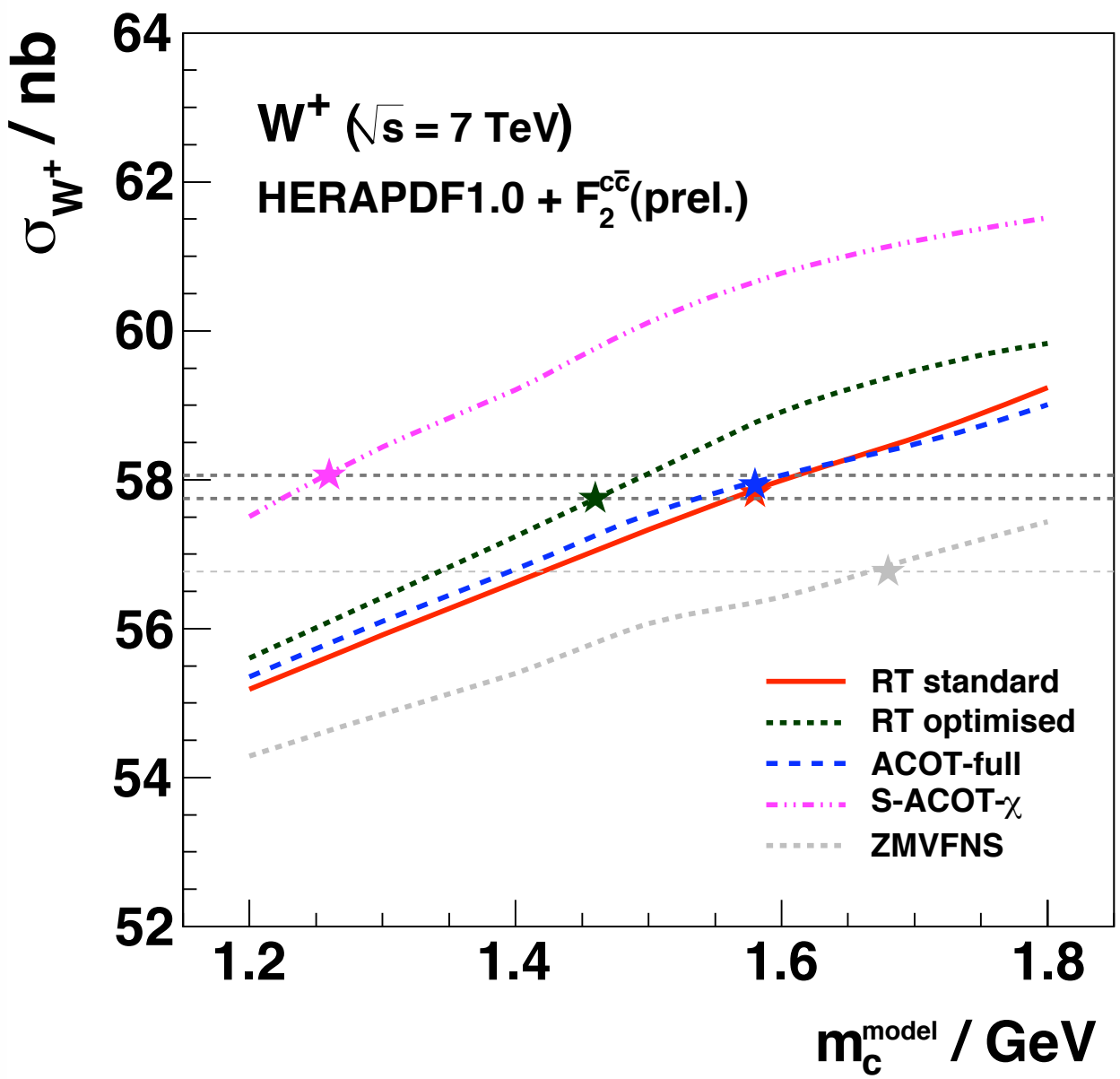


# Effect on LHC predictions

Wide variation in extracted charm mass depending on scheme

Large variation in cross section for fixed mass

However, predictions close when using the appropriate mass for a given scheme



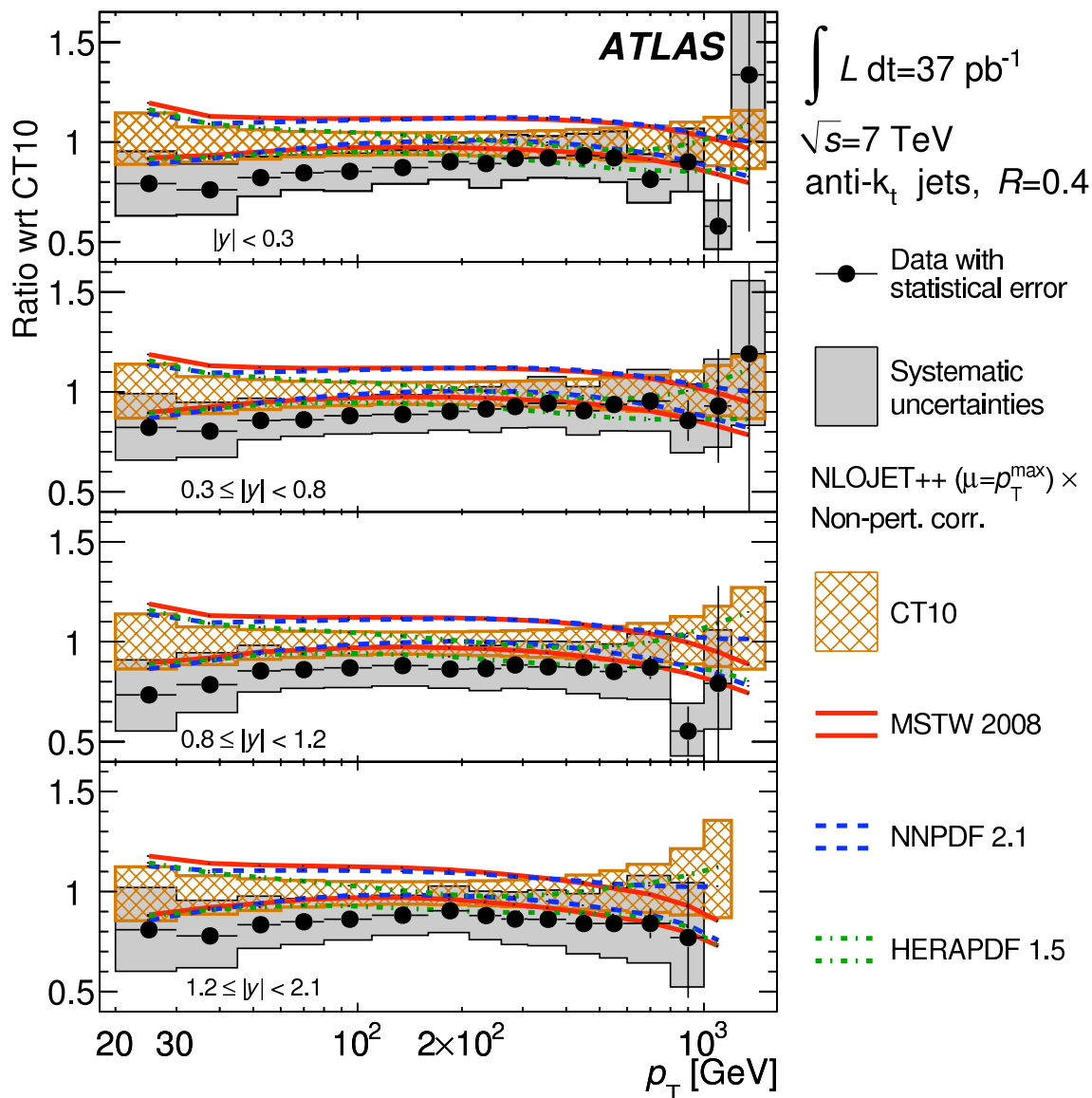
# Effect on LHC predictions

Recent ATLAS results on jet production

Similar comparison between all global PDFs and HERAPDF

The high  $Q^2$  data presented in this talk can only improve these predictions

HERA data crucial to LHC physics





# Discussion and summary





# Discussion and outlook

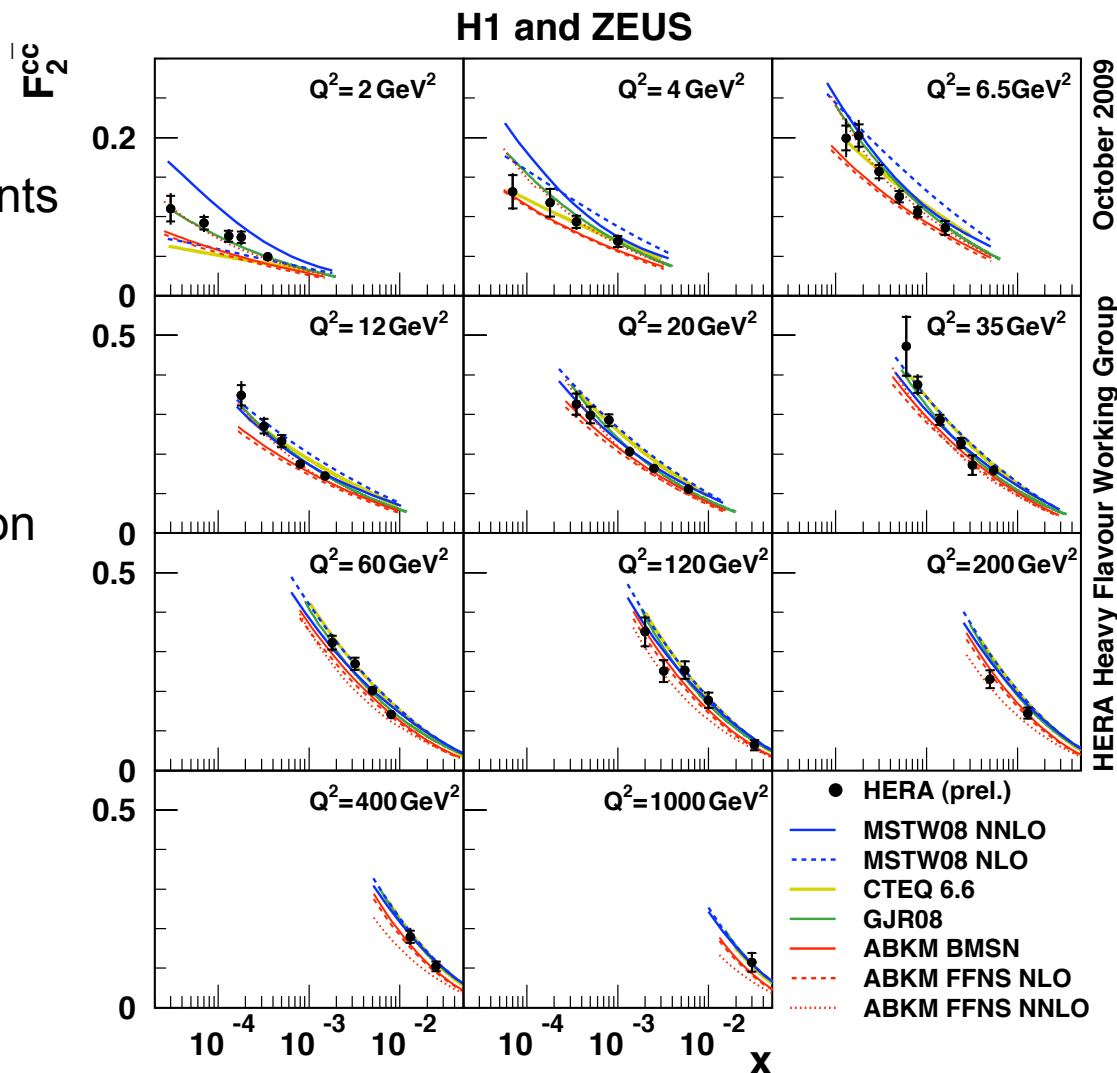
Both H1 and ZEUS have completed the analysis of the inclusive high  $Q^2$  DIS data

Next step is to combine (as was done for HERA I)

Use the data along with HERA I and  $F_L$  measurements in a new HERAPDF fit

Also include HERA jet data, charm measurements

New significant input to the job of constraining the proton PDFs and providing better predictions





# Summary

Final measurements of high  $Q^2$  DIS data presented

Beautiful demonstrations of our understanding of electroweak physics

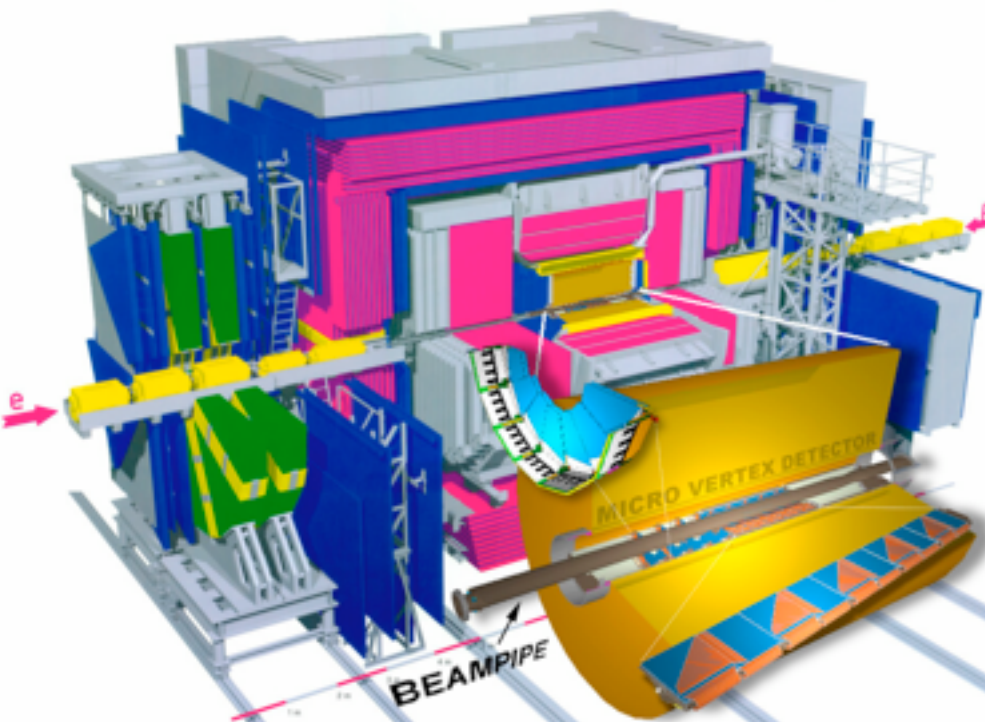
The data is precise and covers a wide kinematic range

They provide *the* crucial constraints on the proton PDFs



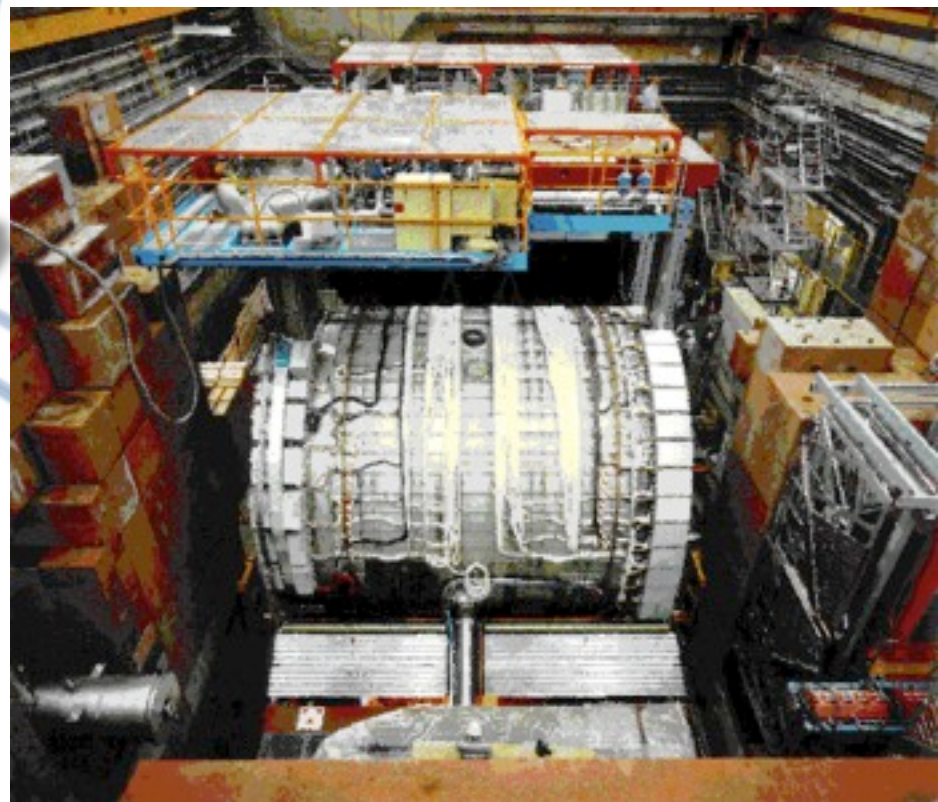
# Back-up

# The H1 and ZEUS detectors



Both large general-purpose detectors:

- Almost hermetic
- Similar to LEP, Tevatron, etc.
- More instrumentation in proton direction



Sub-detectors consist of:

- Electromagnetic and hadronic calorimeters
- Tracking detectors
- Micro-vertex detectors
- Luminosity monitors
- Muon chambers
- ...