Proton structure function measurements at HERA

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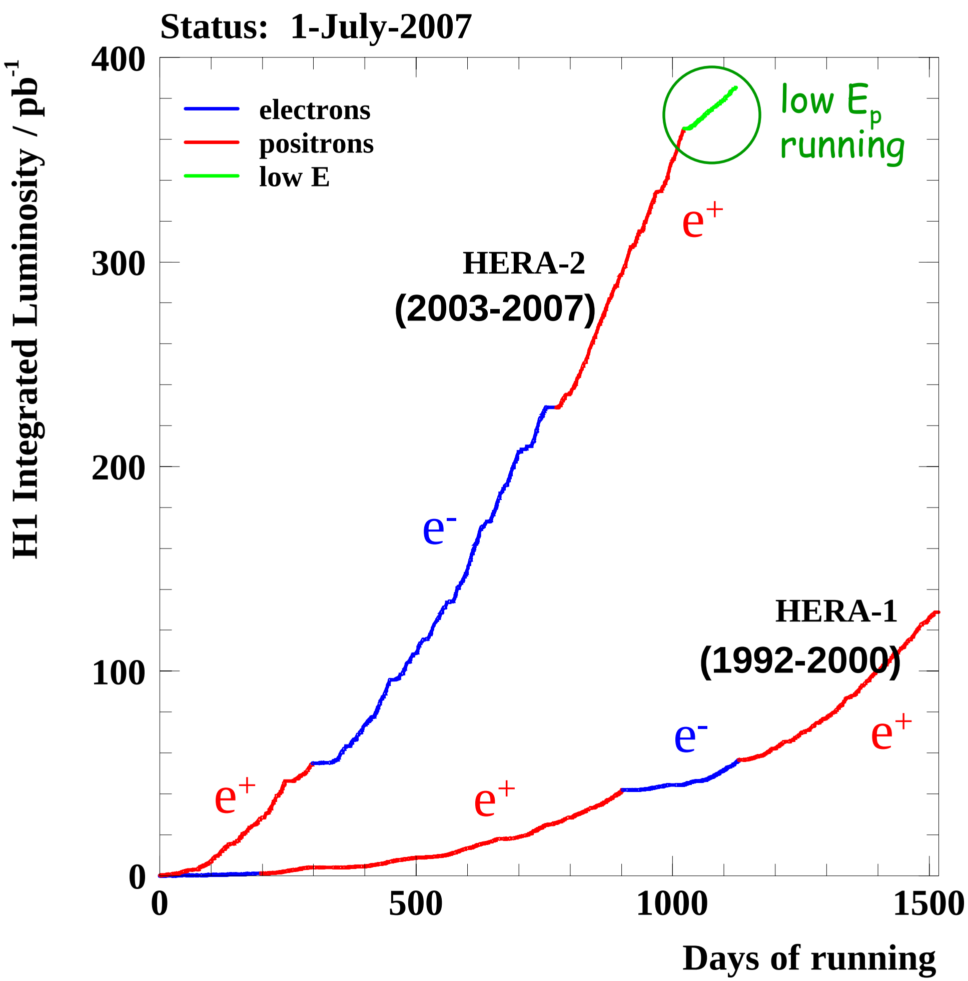
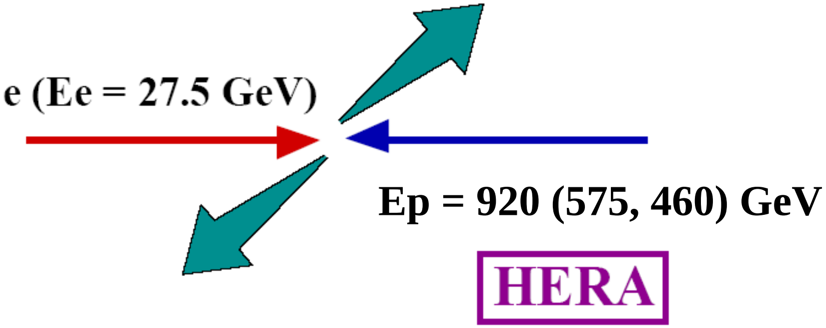
on behalf of H1 and ZEUS

- The HERA ep collider (1992-2007)
- Deep Inelastic Scattering (DIS) / Structure functions (SF)
- Combination of H1 and ZEUS inclusive NC & CC cross sections
- QCD fit to the combined H1 and ZEUS data
- Longitudinal structure function $F_L(x,Q^2)$
- Summary

HERA (1992–2007)

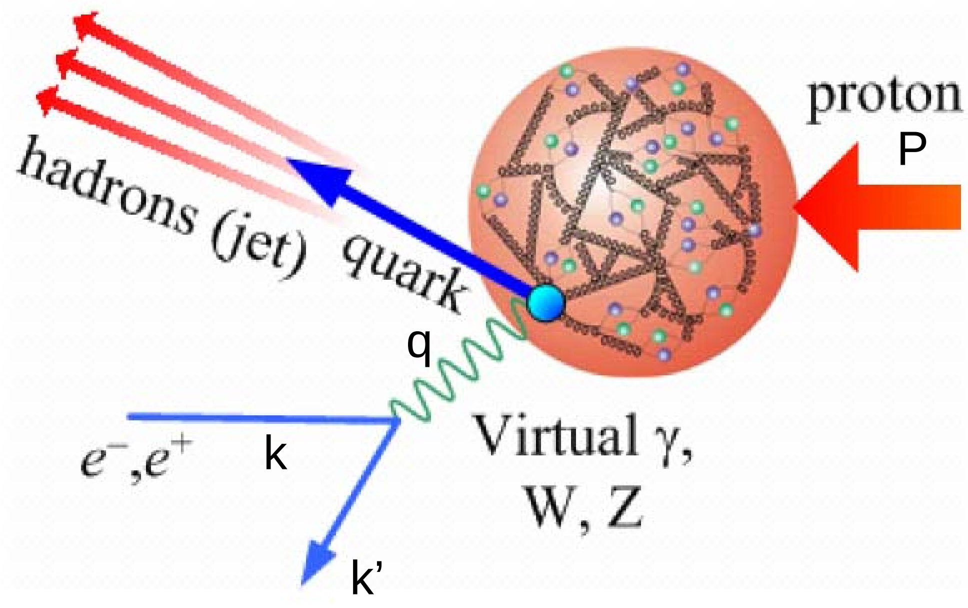




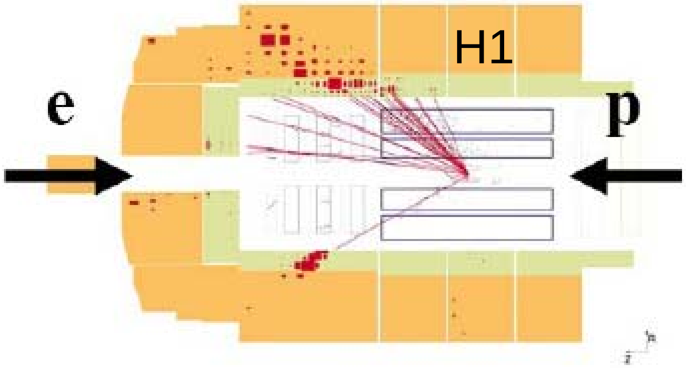
peak luminosity 5 10^{31} cm^{-2} sec^{-1}
Q^2_{max} = 10^5 GeV^2
λ_{min} ~ 1/1000 r_{proton}
longitudinal e-beam polarisation

H1+ZEUS in total ~ 1 fb^{-1}
about equally shared between
- experiments (H1, ZEUS)
- e^+ and e^-,
- positive and negative P_e

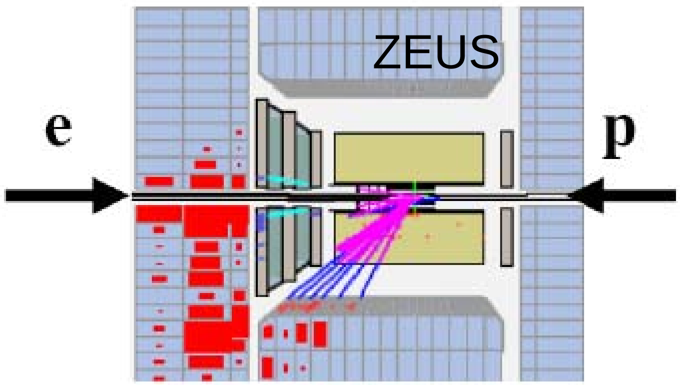
Deep Inelastic Scattering (DIS)



Neutral Current (NC): $e^{\pm} p \rightarrow e^{\pm} X$



Charged Current (CC): $e^{\pm} p \rightarrow \nu X$



$Q^2 = -q^2 = -(k-k')^2$ virtuality of γ^*,Z

$x = Q^2/2(Pq)$ Bjorken x

$y = (Pq)/(Pk)$ inelasticity

$Q^2 = sxy$ $s=(k+P)^2$

Factorisation: $\sigma_{DIS} \sim \hat{\sigma} \otimes pdf(x)$

$\hat{\sigma}$ – perturbative QCD cross section

pdf – universal parton distribution functions

NC: Proton Structure Functions

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

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

dominant contribution :

$$F_2(x,Q^2) = \sum e_{q_i}^2 x(q_i + \bar{q}_i)$$

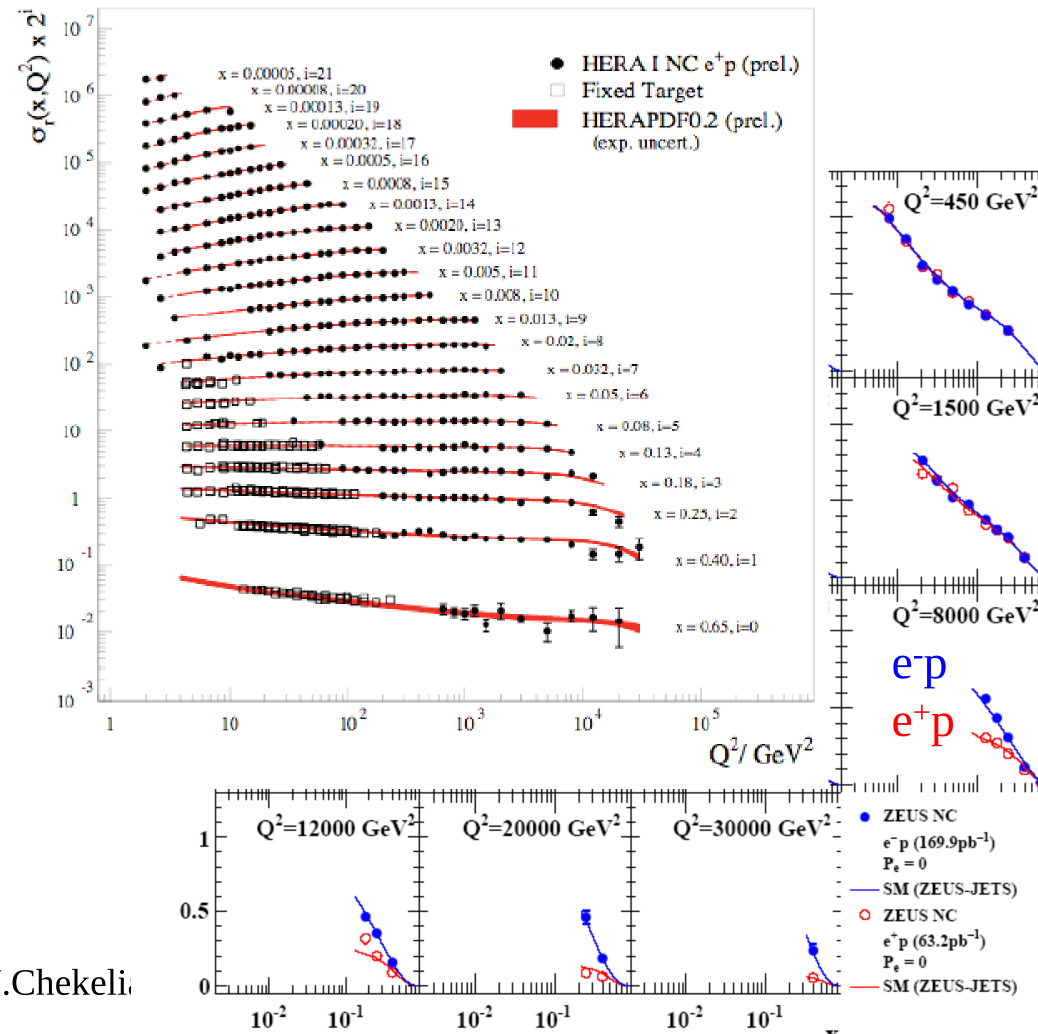
at high Q^2 ($\gtrsim M_Z^2$) :

$$xF_3(x,Q^2) = x\sum B_i(q_i - \bar{q}_i)$$

→ valence quarks

at high y :

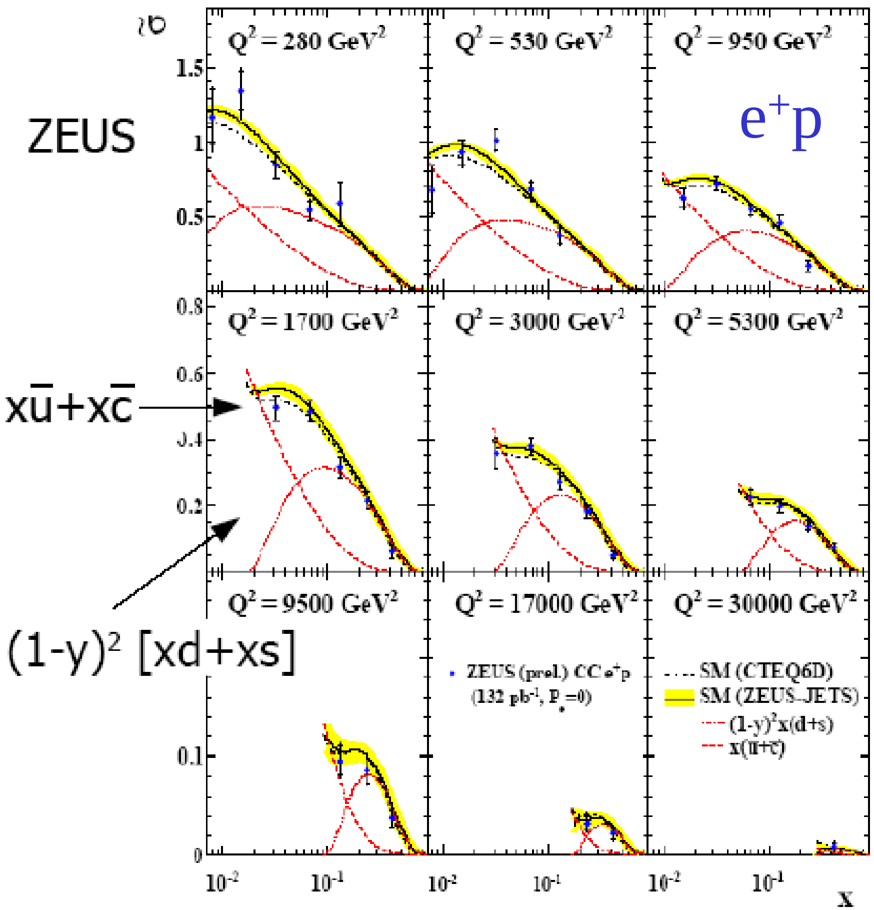
F_L → directly sensitive to gluon



CC: Flavour Separation

$$\frac{d^2\sigma_{CC}(e^\pm p)}{dx\,dQ^2} = \frac{G_F^2 M_W^4}{2\pi x}\frac{1}{(Q^2+M_W^2)^2}\,\underbrace{\frac{1}{2}\left[Y_+W_2 - y^2W_L \mp Y_- xW_3\right]}_{\tilde{\sigma}_{CC}(x,Q^2)}$$

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



The CC e^+p cross section
- determines d quark at high x
  (little sensitivity from NC)

$$\tilde{\sigma}_{CC}^{e^+p}(x,Q^2) \sim (\bar{u}+\bar{c}) + (1-y)^2(d+s)$$

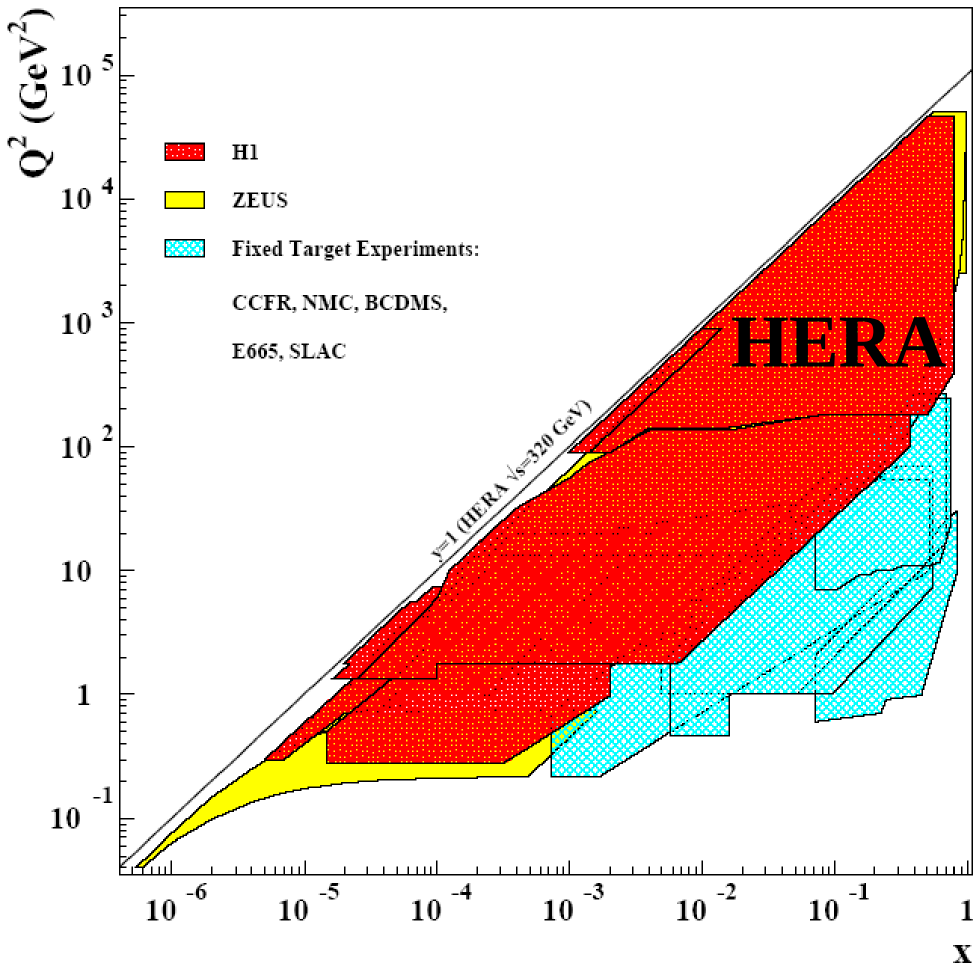
The CC e^-p cross section
- dominated by u quark

$$\tilde{\sigma}_{CC}^{e^-p}(x,Q^2) \sim (u+c) + (1-y)^2(\bar{d}+\bar{s})$$

- constrain d (u) quark density
- free of nuclear corrections
  and isospin assumptions

Kinematic Reach in x and Q^2

HERA: 6 decades both in x and in Q^2



All HERA I (1994-2000) inclusive NC & CC analyses are completed and published

- for Q^2 < 100 GeV^2 the results are final

HERA II (203-2007) NC & CC at high Q^2 are beeing analysed / published

- including polarisation dependences

H1 and ZEUS performed new NLO QCD fits (H1PDF 2009, ZEUS09)

→ combination of H1 and ZEUS NC & CC data (HERA I)

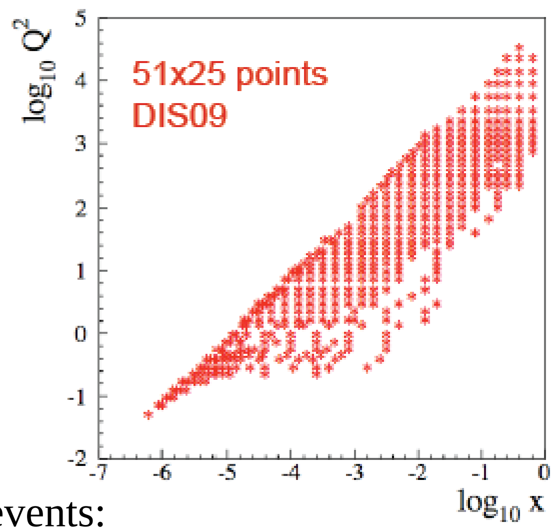
→ NLO QCD fit using combined H1 & ZEUS data (HERAPDF0.2)

→ F_L measurements using low E_p data

Combination of H1 and ZEUS

The goal is to have "the unique HERA data set" which includes expert knowledge in the treatment of the correlations between many individual data sets from H1 and ZEUS
→ most precise, complete and easy to use

Combine inclusive unpolarised NC & CC cross sections from H1 and ZEUS at HERA I (1994-2000)
→ ***all HERA I analyses are completed and published.***
Exploit differences between H1 and ZEUS in detectors, methods and systematics to "cross-calibrate", and hence to reduce the systematic uncertainties.



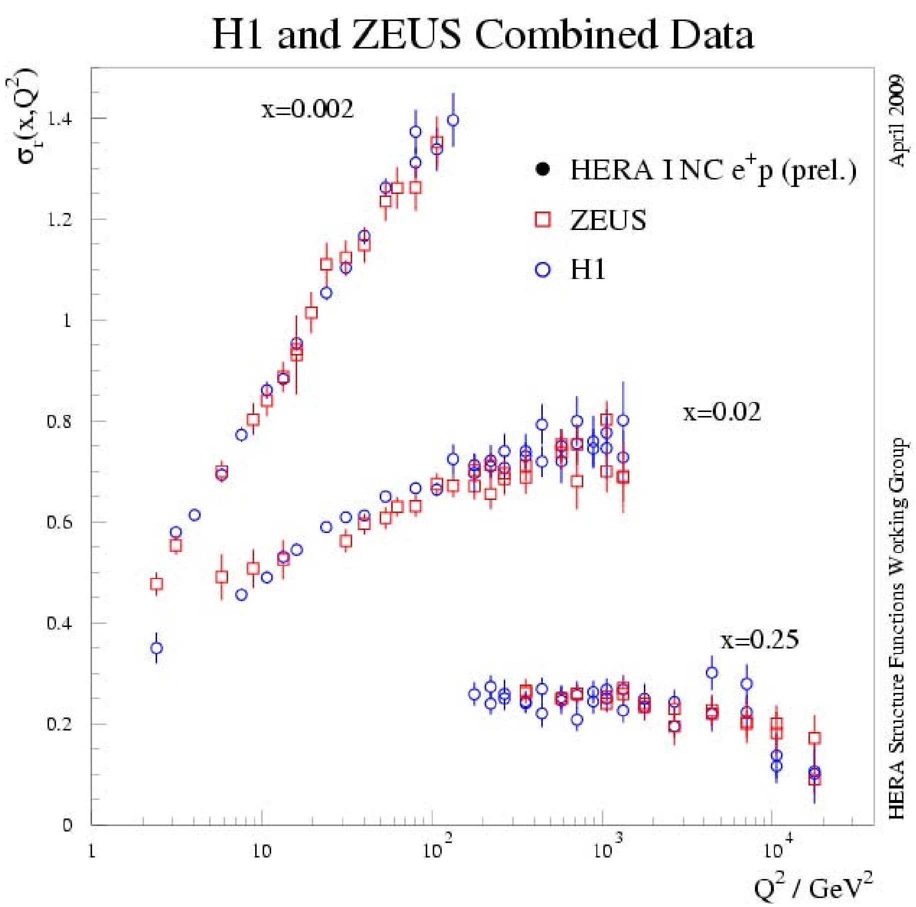
- for each channel move measured points to a common x-Q^2 grid
- correct E_{pbeam}=820 GeV data to E_{pbeam}=920 GeV
- average H1 and ZEUS points at given x,Q^2 at y < 0.35
- keep all data points at y > 0.35, modifying them to account for the determined shifts in the correlated systematic sources.

The averaging exploits a concept of correlated syst. errors, assuming that systematic uncertainties are proportional to expected values and statistical uncertainties are defined by sqrt of expected number of events:

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

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

Combination of H1 and ZEUS data from HERA I



1402 points are combined to 741 unique cross section measurements

χ^2/ndf = 637/656

→ the original H1 and ZEUS data are fully consistent

combined data set:
110 corr. syst. sources from individual data sets
3 correlated errors from averaging procedure:
- difference between "multiplicative" treatment of errors and "additive"
- photoproduction background
- hadronic energy scale

more than just double statistics:
→ significant reduction of systematics and little difference then how to treat 110 corr. syst. sources in QCD fits - the simplest approach is to added them in quadrature to the uncorrelated errors

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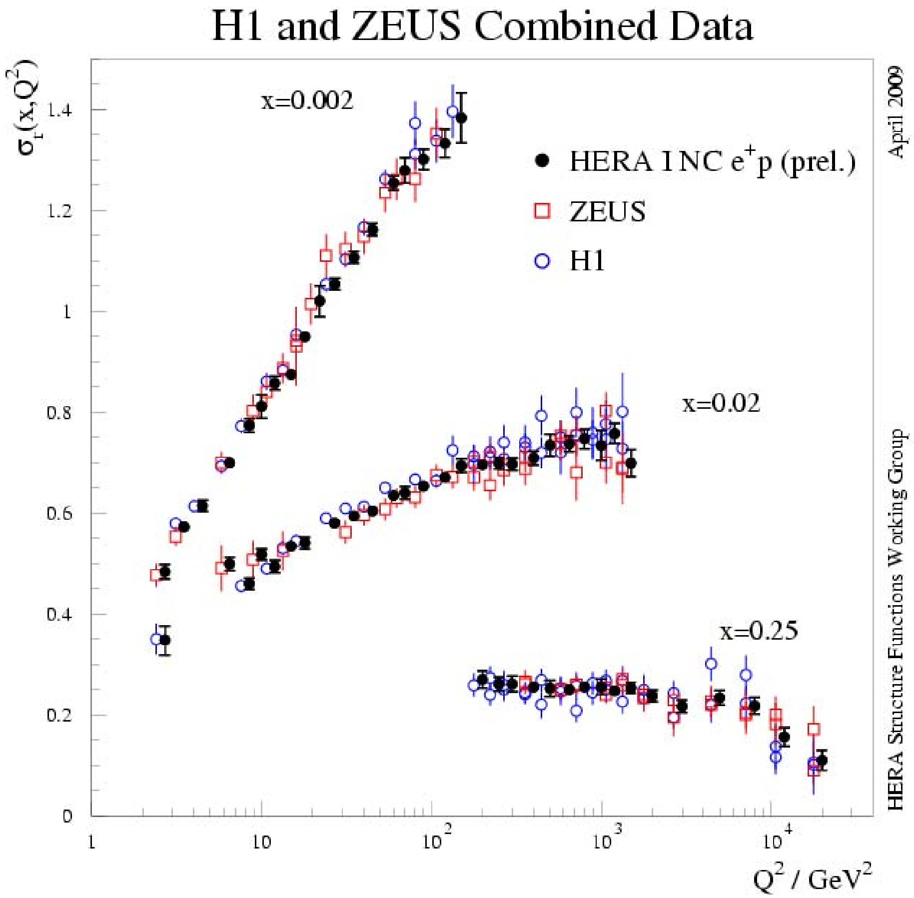

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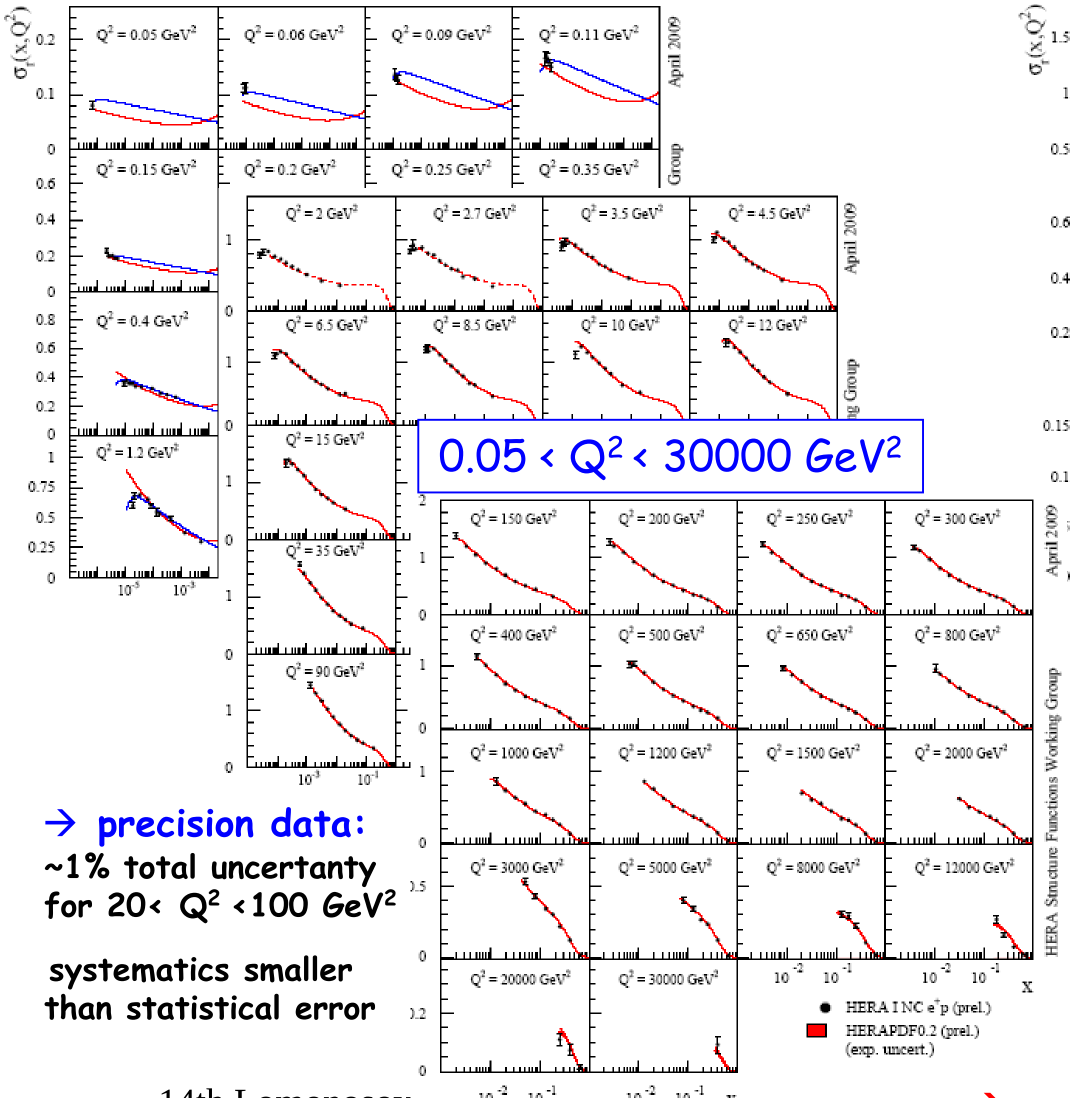
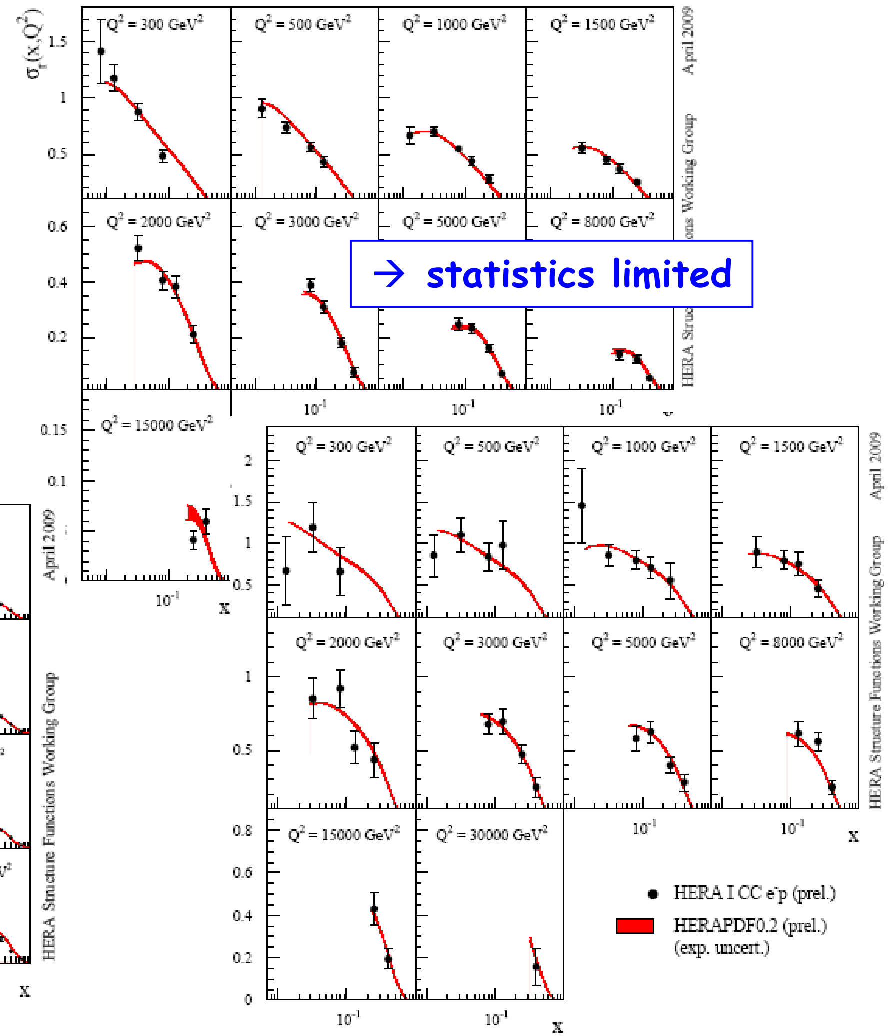
Combined H1 and ZEUS data from HERA I

NC $e^{+/-}p$

CC $e^{+/-}p$



0.05 < Q^2 < 30000 GeV^2



→ statistics limited

→ precision data:

~1% total uncertanty for 20< Q^2 <100 GeV^2

systematics smaller than statistical error

→ can be used as a sole input to the QCD Fit

NLO QCD fit using combined H1 and ZEUS data

input: the combined H1 and ZEUS inclusive NC & CC e^+p & e^-p data from HERA I

next-to-leading order (NLO) DGLAP in MS scheme for evolving PDFs to arbitrary Q^2

improved theoretical treatment of heavy flavours which takes the quark masses into account
→ SF calculations in General-Mass Variable Flavour Scheme (GMVFNS): massive NLO splitting and coefficient functions according to Thorne-Roberts VFNS 2008

renormalisation and factorisation scales : Q^2

Q^2_{min} = 3.5 GeV^2, M_c=1.4 GeV, M_b=4.75 GeV, $\alpha_s(M_Z)$=0.1176 (PDG 2006)

Paramaterisation form at starting scale Q_o^2=1.9 GeV^2 :

$$xf(x,Q_o^2) = Ax^B(1-x)^C(1+Dx+Ex^2)$$

$x\bar{U}=x\bar{u}+x\bar{c}$, $x\bar{D}=x\bar{d}+x\bar{s}+x\bar{b}$

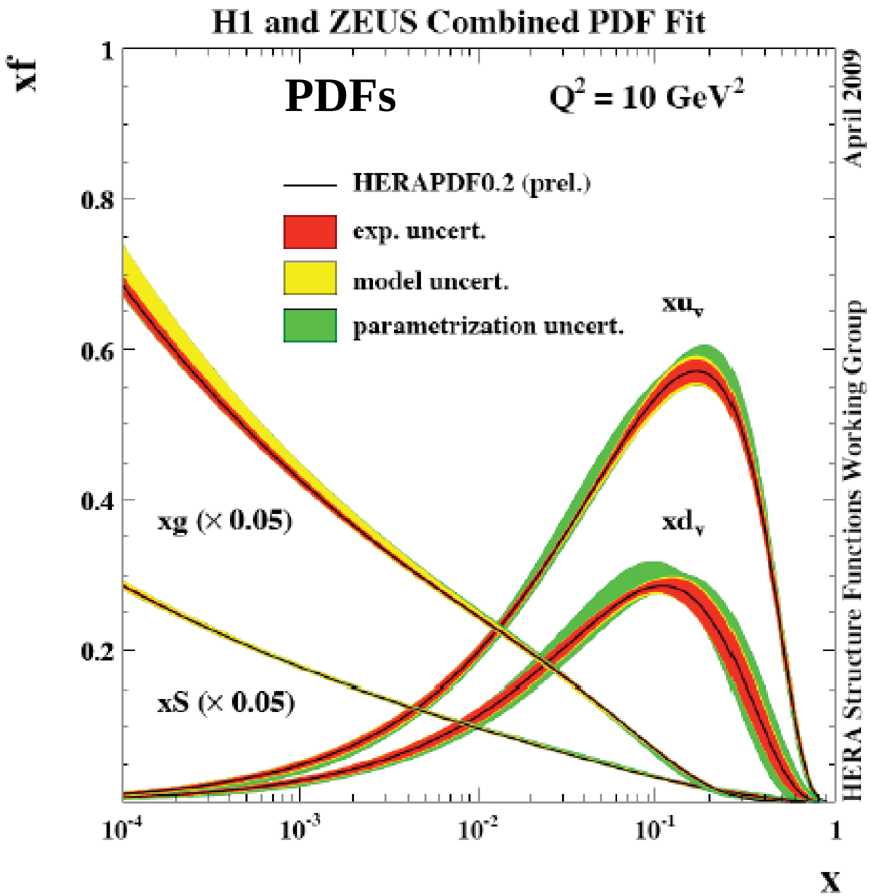
$c\bar{c}$, $b\bar{b}$ are genarated dynamically

PDF	A	B	C	D	E
xg	sum rule	FIT	FIT	-	-
xu_{val}	sum rule	FIT	FIT	-	FIT
xd_{val}	sum rule	$=B_{u_{val}}$	FIT	-	-
$x\bar{U}$	$\lim_{x\to 0}\bar{u}/\bar{d} \to 1$	FIT	FIT	-	-
$x\bar{D}$	FIT	$=B_{\bar{U}}$	FIT	-	-

The optimum number of parameters is taken from saturation in the improvement of the χ^2 require all PDFs to be positive and q_{val} > qbar at high x

→ 10 free parameters for the central fit: χ^2/ndf=576/592

HERAPDF0.2



gluon and sea are devided by a factor of 20

experimental uncertainty (red):

tolerance $\Delta\chi^2 = 1$

110 syst. errors are combined in quadrature with unc. errors

3 sources of errors from the averaging procedure are offset

→ small effect when 110 syst. errors treated as correlated:
different methods of treating the correlated systematic errors (Hessian, offset, add in quadrature) do not make much difference

model uncertainty (yellow):

variations of input assumptions

→ added in quadrature

Variation	Central	Lower	Upper
m_b	4.75	4.3	5.0
Q^2_{min}	3.5	2.5	5.0
f_s	0.31	0.23	0.38
m_c	1.4	1.35	1.5
Q^2_0	1.9	1.5	2.5

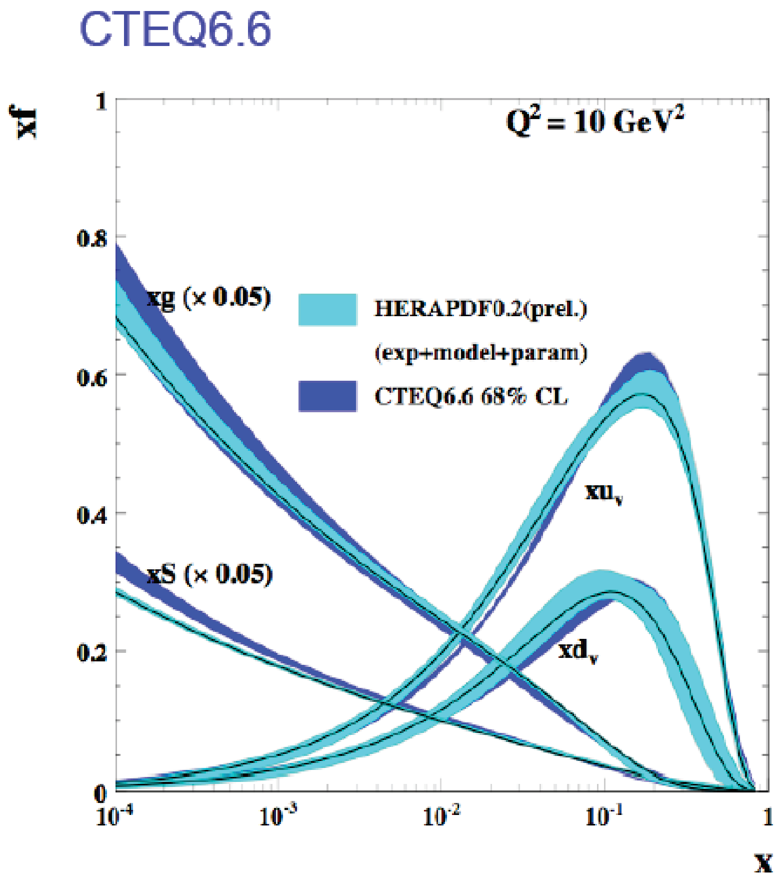
parameterisation uncertainty (green):

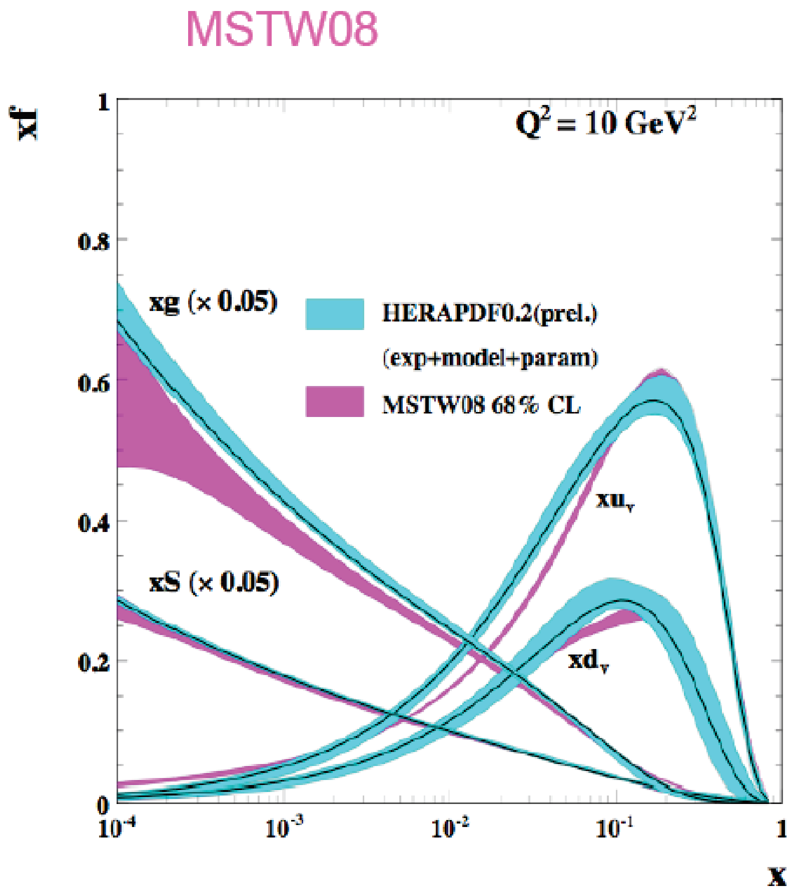
make envelope from other 10 parameter fits and 11 parameter fits with $E_u > 0$ and an extra D or E.

Positivity of PDFs and q_{val} > qbar at high x are not required.

→ effect is mostly at large x

Comparison with CTEQ and MSTW

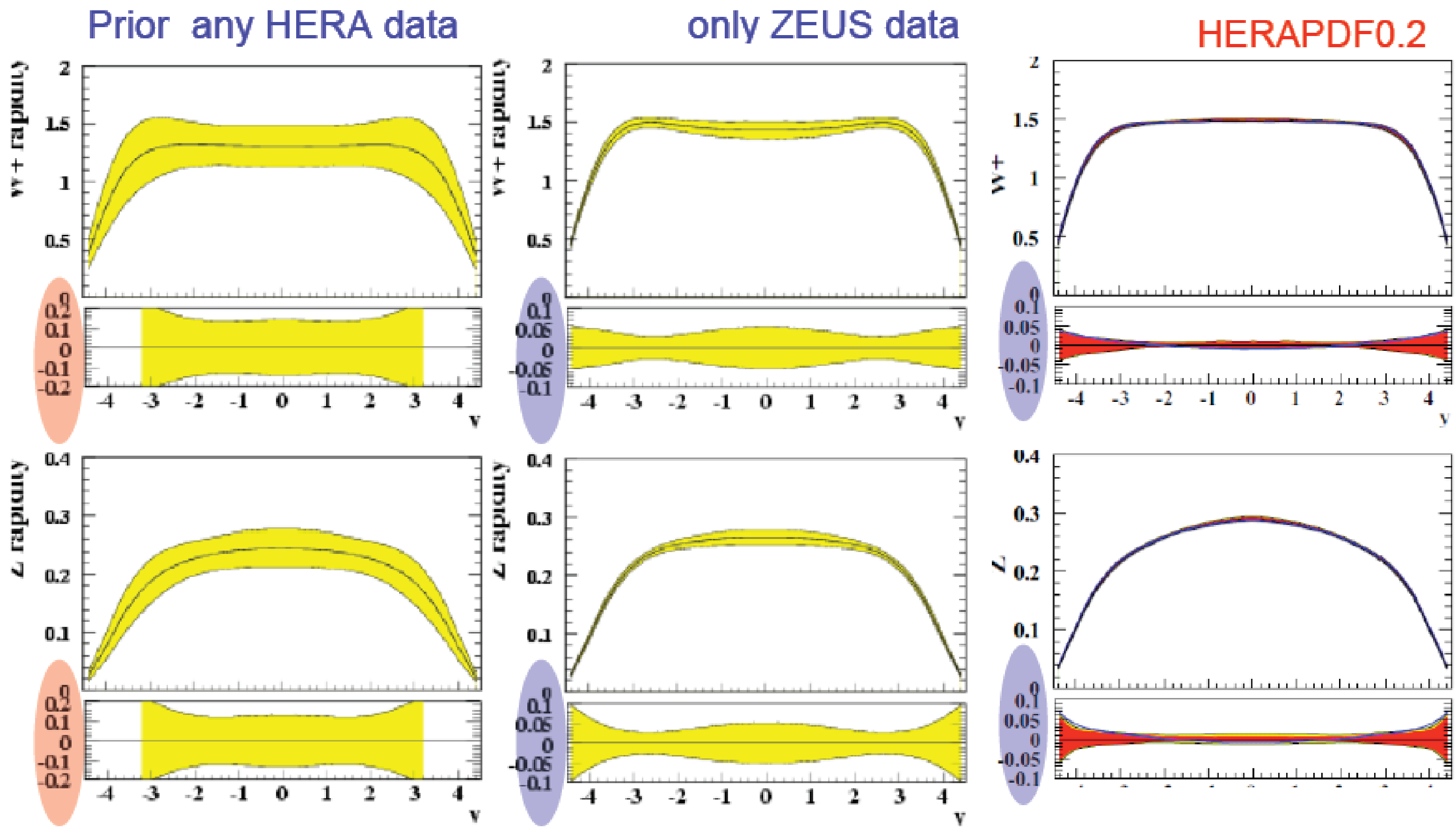




- comparison at 68% CL
- HERA QCD fit: impressive precision at low x

Projection to the LHC

Rapidity dependence of W^+ and Z production (at 14 GeV)



errors include only experimental uncertainty

→ experimental (total) uncertainty at central rapidity is ~1% (~2%) when the combined HERA data are used

The longitudinal structure function $F_L(x,Q^2)$

- F_L is a pure QCD effect which allows to make critical tests of the perturbative QCD framework used for pdf determinations
- F_L is directly sensitive to gluon density

$$F_2 \sim \sigma_L^{\gamma p} + \sigma_T^{\gamma p}\,,\quad F_L \sim \sigma_L^{\gamma p} \quad \rightarrow \quad 0 \leqslant F_L \leqslant F_2$$

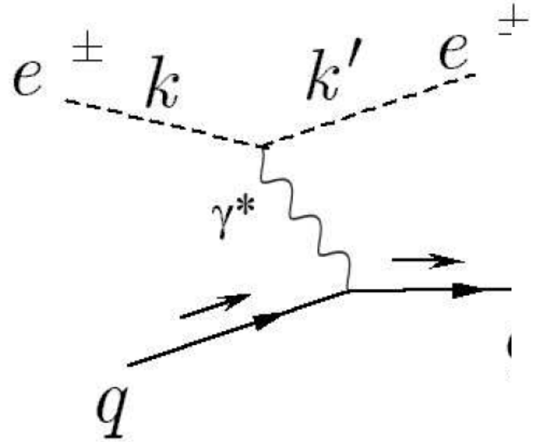
in QPM

due to helicity and angular momentum conservation for spin ½ quarks

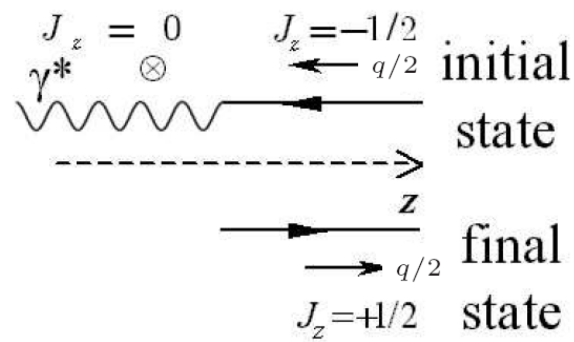
$$F_L \sim \sigma_L^{\gamma p} = 0$$

$F_L = F_2 - 2xF_1 = 0$

Callan-Gross relation



Breit frame:



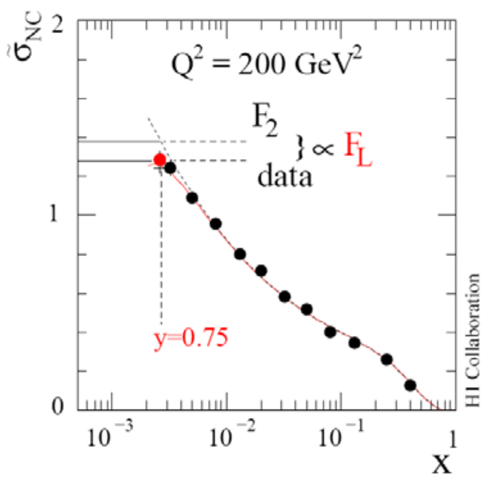
in QCD:

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

Measurement strategy for F_L

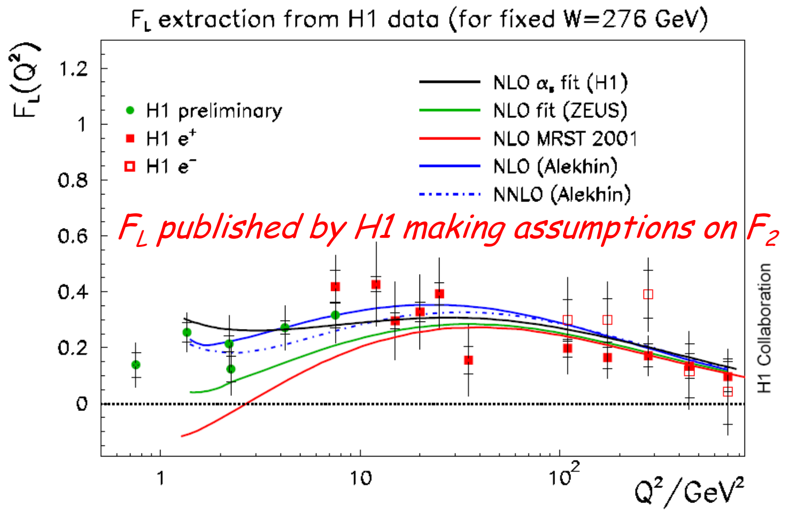
$$\tilde{\sigma}_{NC} = \frac{d^2\sigma^{ep}_{NC}}{dx\,dQ^2} \Big/ \left(\frac{2\pi\alpha^2}{xQ^4} Y_+\right) = F_2 - \frac{y^2}{1+(1-y)^2} F_L$$

sensitivity to F_L only at high y



→ one possible way:

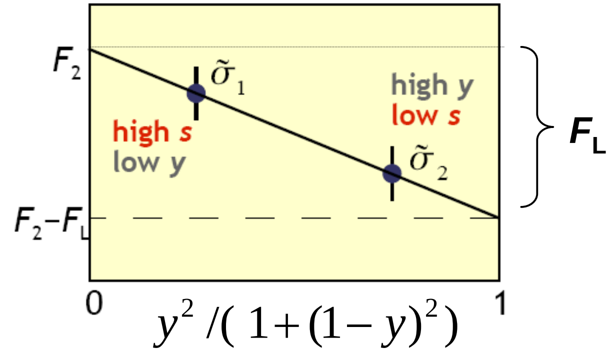
measure σ at high y and assume F_2



→ *free from theoretical assumption:*

measure σ at the same x & Q^2 and different y by changing the proton beam energy :

$y = Q^2/4E_pE_ex$ (E_p = 460, 575, 920 GeV)

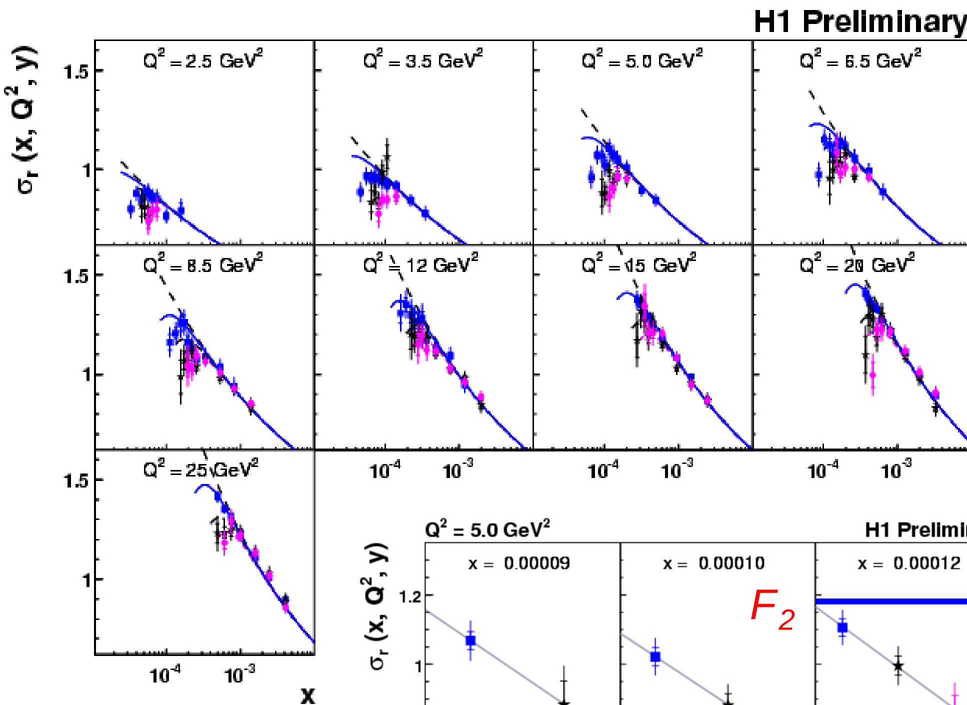


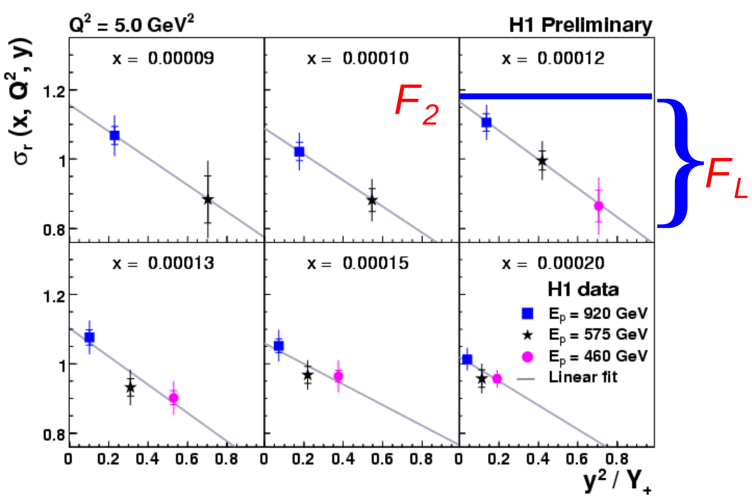
NC cross sections and F_L & F_2

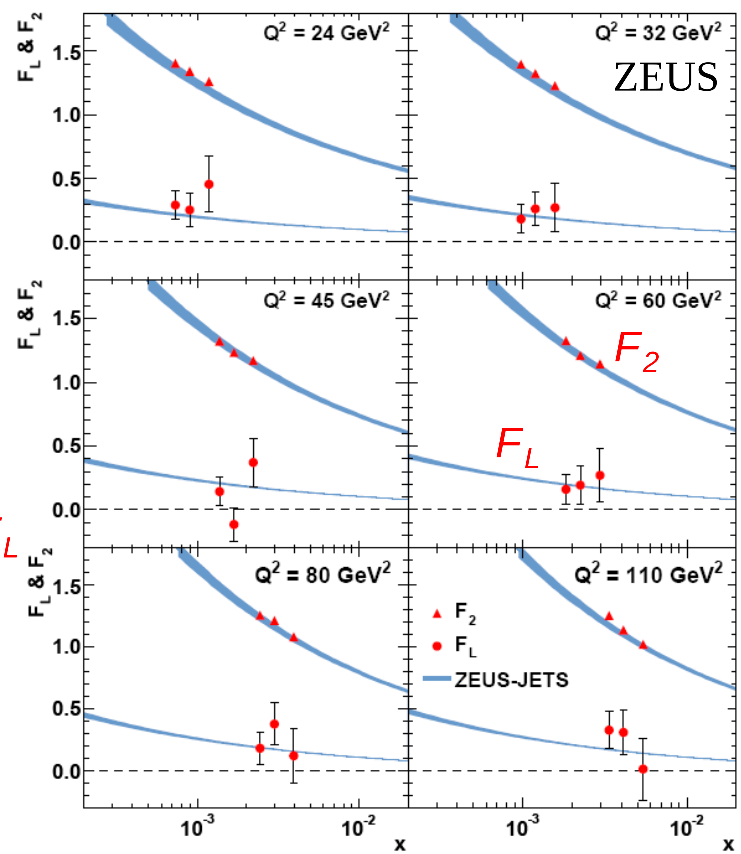
E_p= 460,575,920 GeV

$$\tilde{\sigma}_{NC} = F_2 - y^2/(1+(1-y)^2)\ F_L$$

→ determine F_L and F_2 from linear fits at each x and Q^2



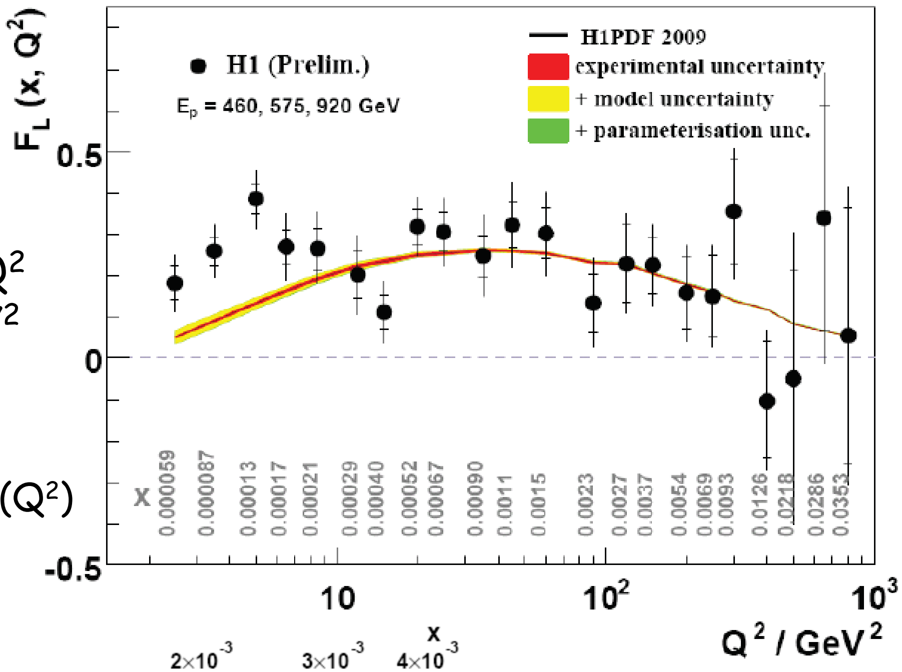




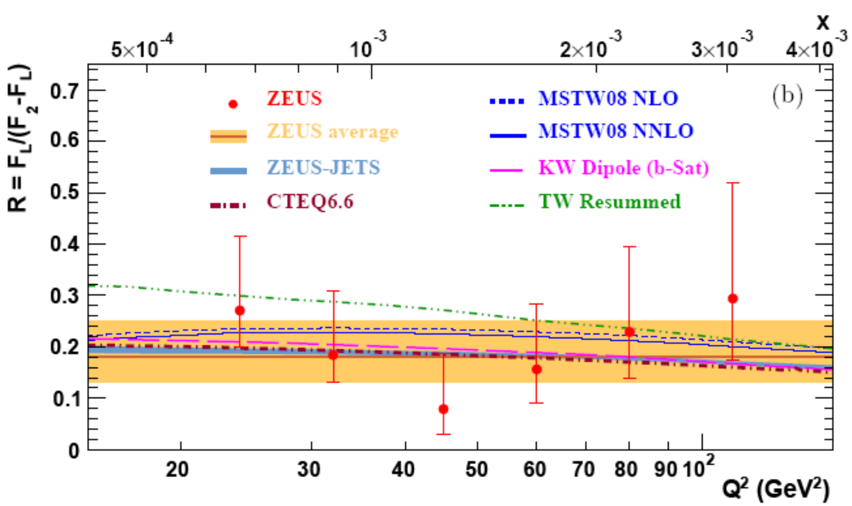
$F_L(Q^2)$ and recent theory predictions

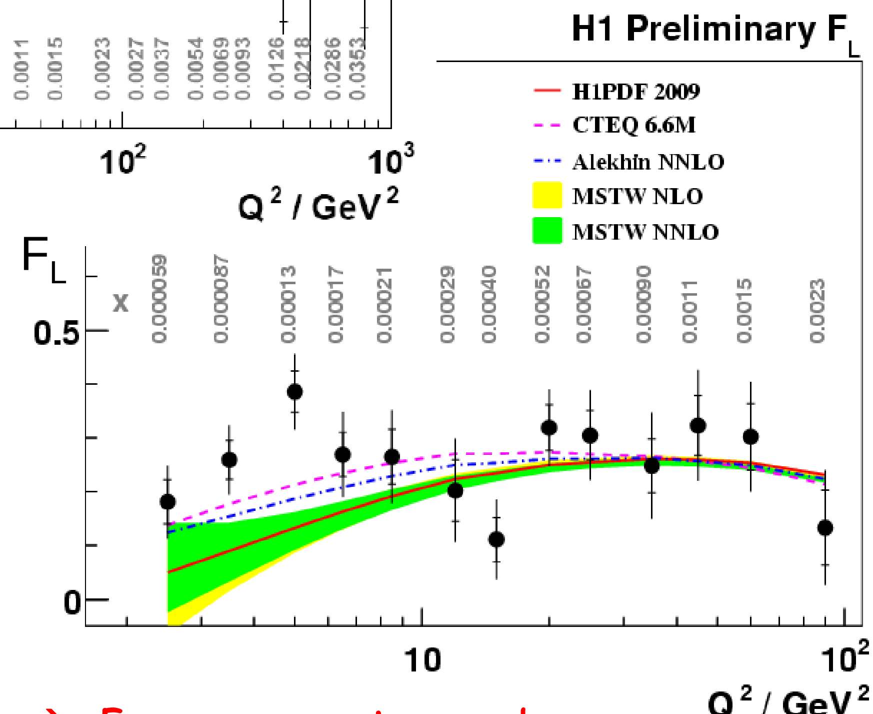
F_L is measured for Q^2 from 2.5 to 800 GeV^2

x value for each $F_L(Q^2)$



$F_L(Q^2)$ is above zero and consistent with NLO QCD at Q^2 > 10 GeV^2





→ averaged $R=F_L/(F_2-F_L)=0.18+0.07-0.05$

→ F_L measurements are above some NLO QCD calculations at Q^2 < 10 GeV^2

Summary

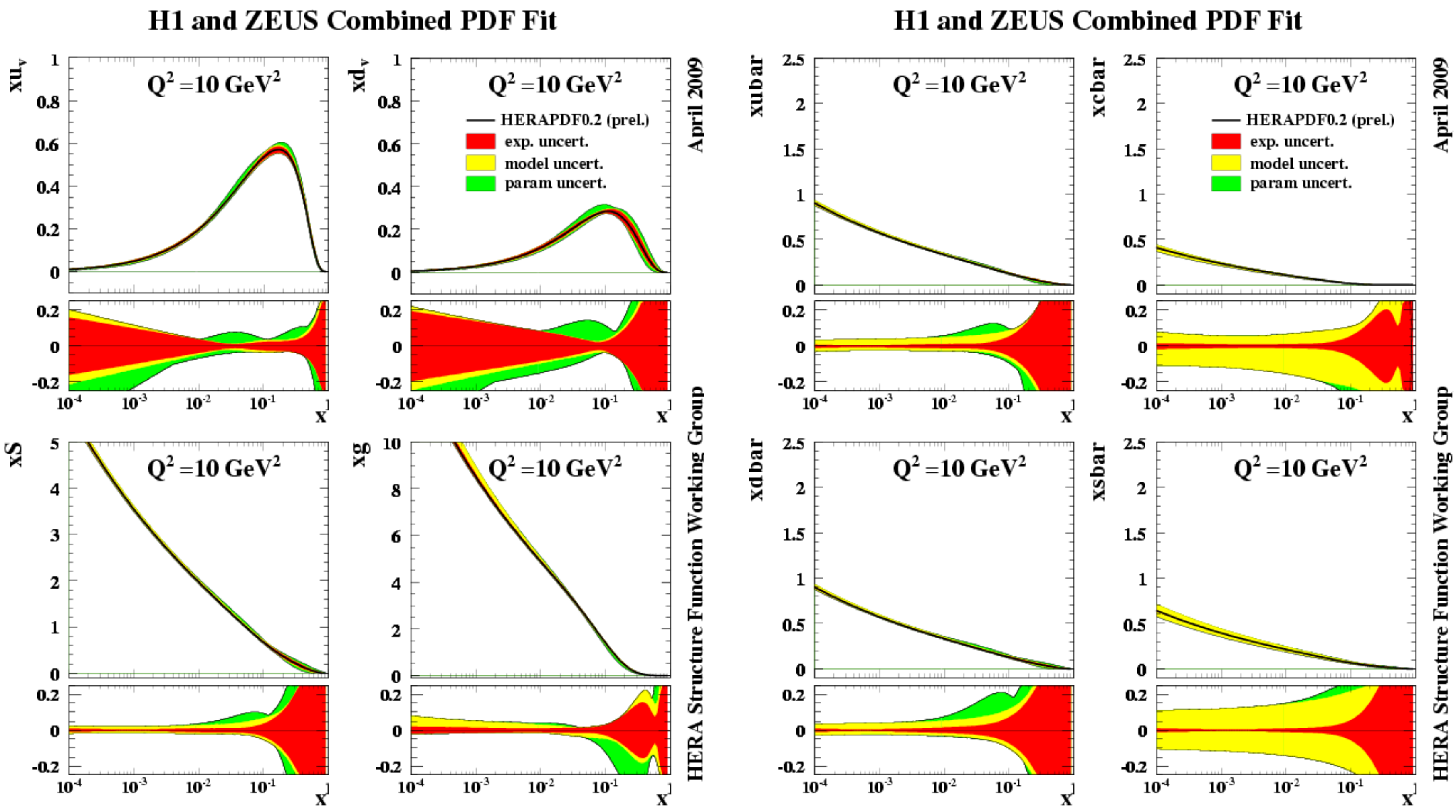
HERA (1992-2007) finished operation two years ago, after 15 years of data taking
- → all HERA I (1994-2000) NC & CC inclusive analyses are completed and published
- → HERA II (2003-2007) analyses are in progress / beeing published

A model-independent averaging method has been developed to combine H1 and ZEUS inclusive NC & CC cross section measurements (applied to the final HERA I data)
- → unique HERA I data set - complete, precise and easy to use
- → significant improvement of systematics (more than just double statistics)

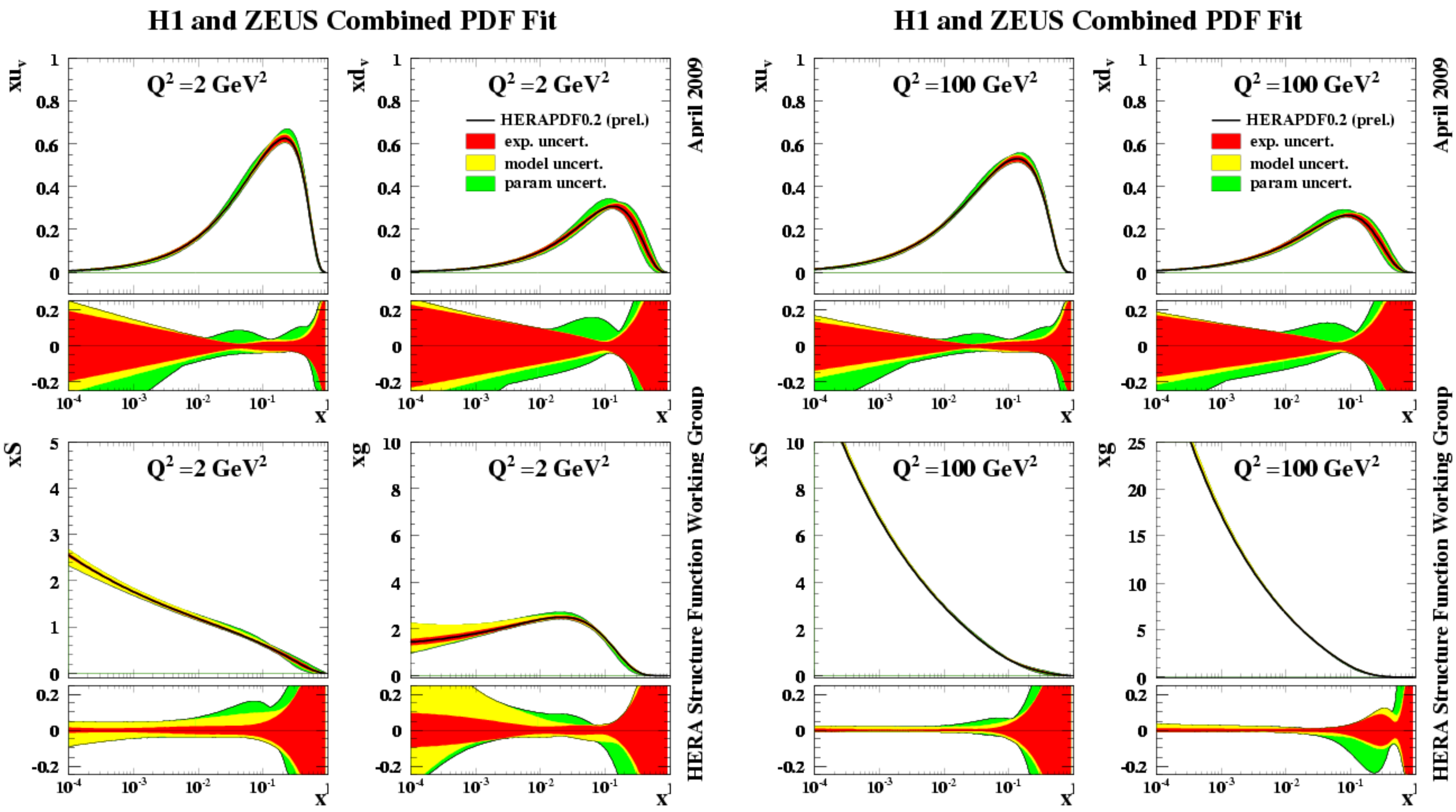
HERAPDF0.2 is the NLO QCD fit to the combined H1 and ZEUS data from HERA I
- → improved theoretical treatment for heavy flavours (TR-VFNS)
- → model and PDF parameterisation uncertainties are considered
- → getting ready for precise prediction at the LHC

The longitudinal structure function $F_L(x,Q^2)$ is measured at HERA for $2.5 \leqslant Q^2 \leqslant 800$ GeV^2 in a model independent way using low E_p data
- → F_L is consistent with NLO QCD at $Q^2 > 10$ GeV^2 and with $R=F_L/(F_2-F_L) = \sim 0.2$
- → some NLO QCD calculations are below F_L measurements at $Q^2 < 10$ GeV^2

HERAPDF0.2 : PDFs at $Q^2 = 10\ GeV^2$



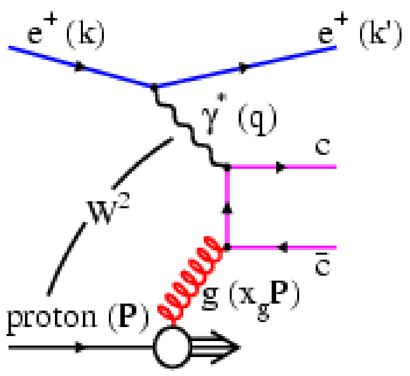
HERAPDF0.2 : PDFs at Q^2 =2,100 GeV^2



Charm and Beaty distribution functions

- charm contribution at HERA up to 25-30%
- beauty PDF is important for LHC : bb → H

Boson Gluon Fusion (BGF)



→ c,b dynamically produced
→ compare predictions with c,b data at HERA

NLO QCD predictions for heavy flavour production agree well with the measurements in DIS