Proton parton densities : HERAPDF

Matthew Wing (UCL)
On behalf of the H1 and ZEUS Collaborations

- Motivation, experiments and basics
- Combined measurements of deep inelastic scattering
- HERAPDF : PDFs based on HERA data only
- HERAPDF for other colliders and compared to other PDFs
- Discussion and summary

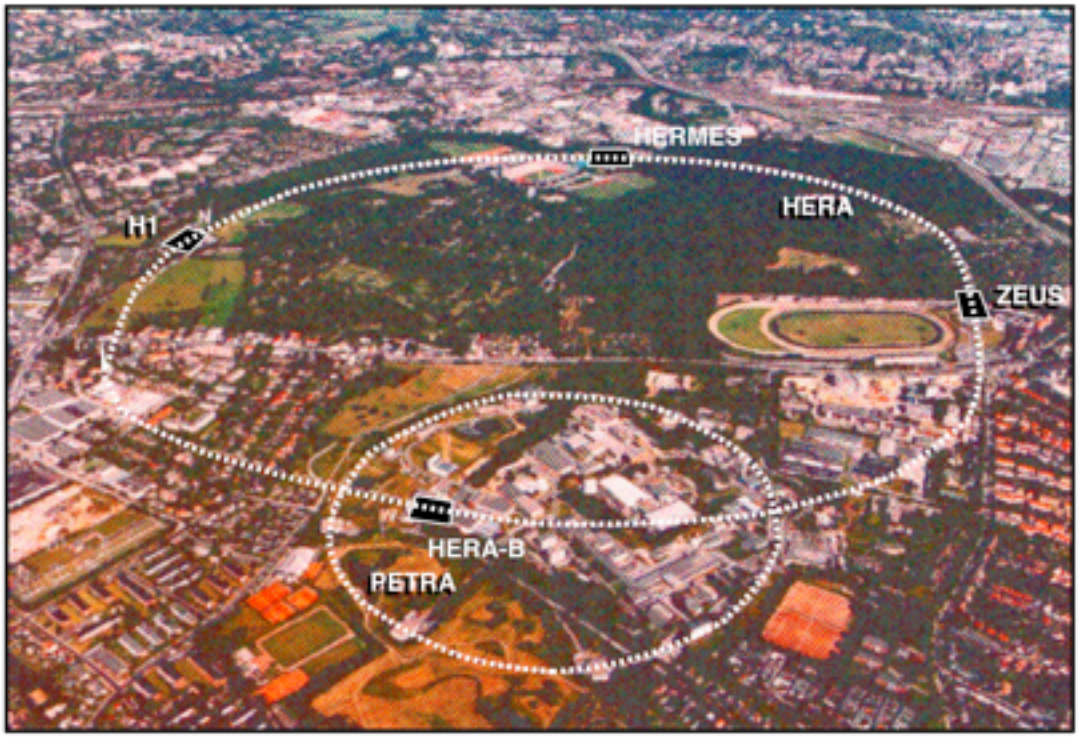
Hadron Collider Physics Conference, Toronto, 23–27 August 2010

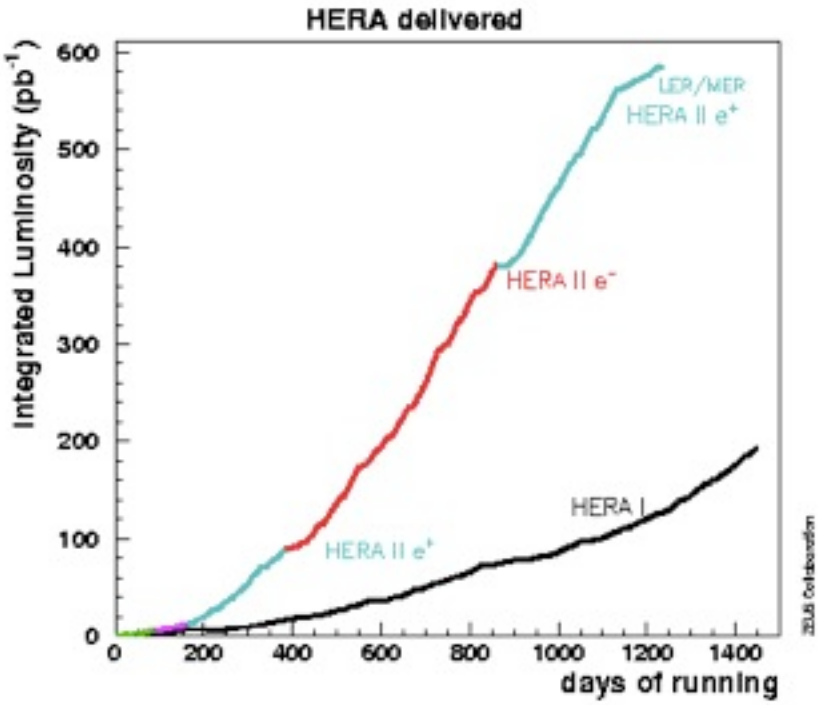
Motivation

Want to understand the structure of the proton :

- Do quarks have substructure or are they truly elementary ?
- Confinement, saturation ?
- 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.
- Measure the deep inelastic cross section at HERA, combine data and extract PDFs using HERA data alone :
    - What do they look like and how precise are they ?
    - How do they compare with other extractions by theoretical groups ?
    - How well do they describe Tevatron (and LHC) data ?
    - What is their impact at the LHC ?

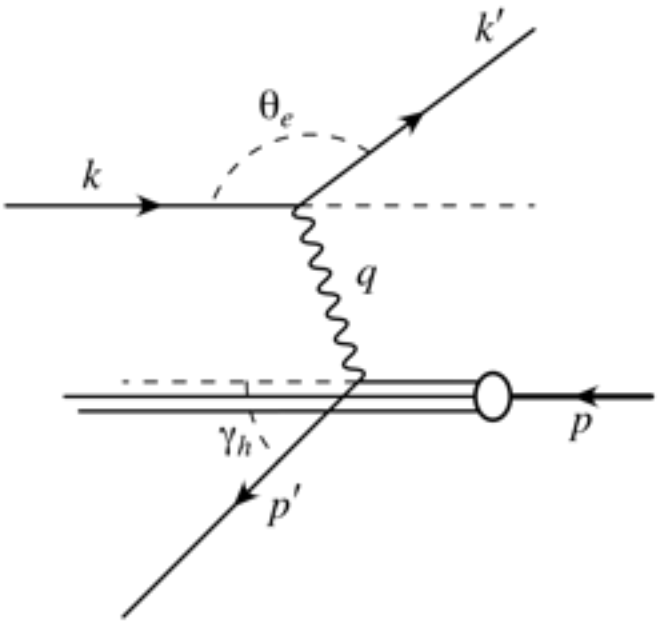
The HERA collider





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

Deep inelastic scattering : definitions



Momentum transfer :

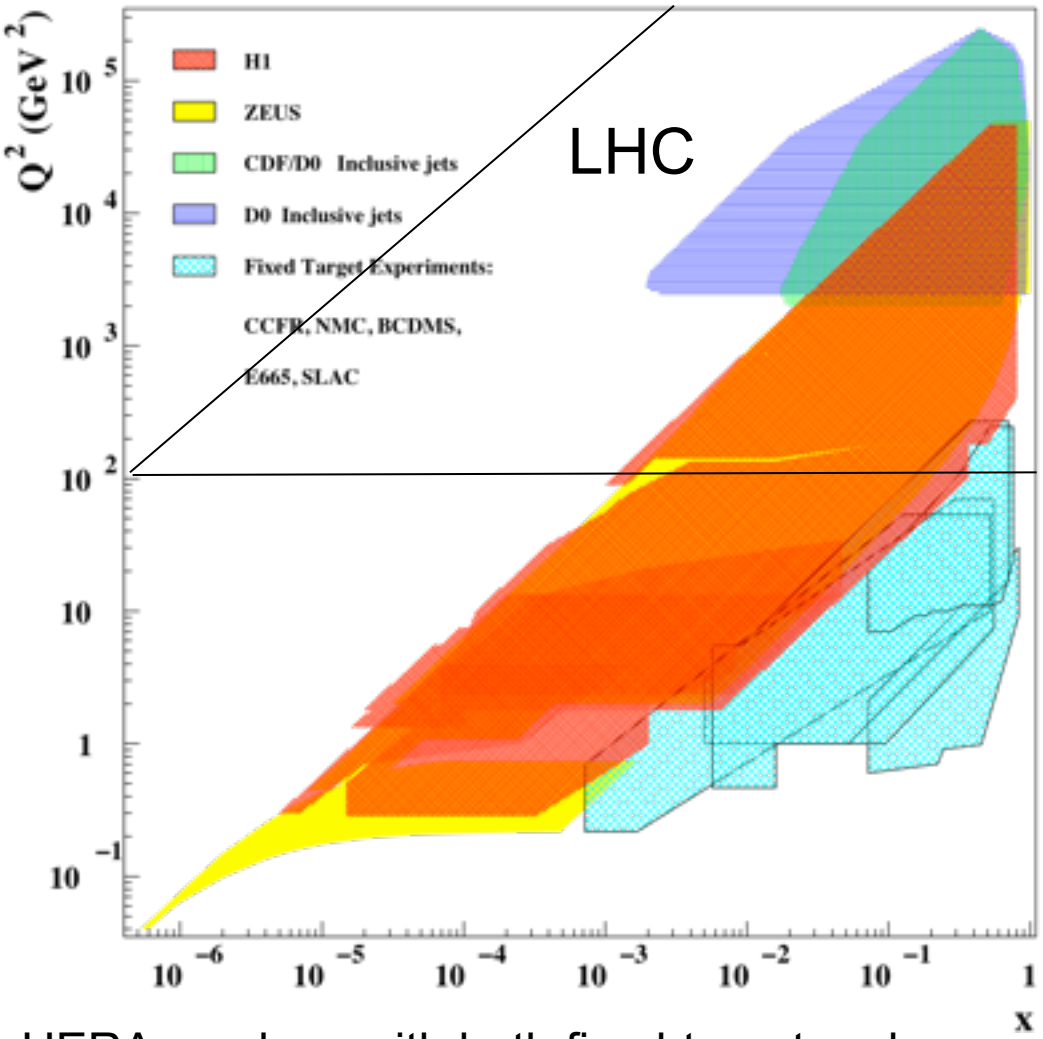
$$Q^2 = -q^2 = -(k-k')^2$$

Momentum fraction carried by struck parton :

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

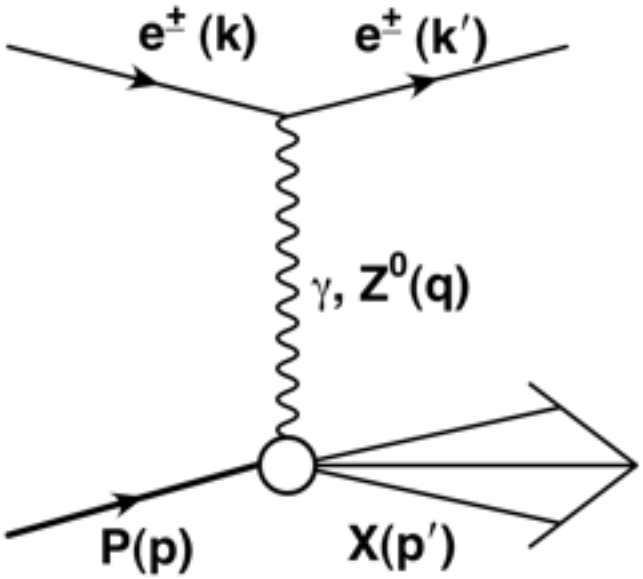
Inelasticity :

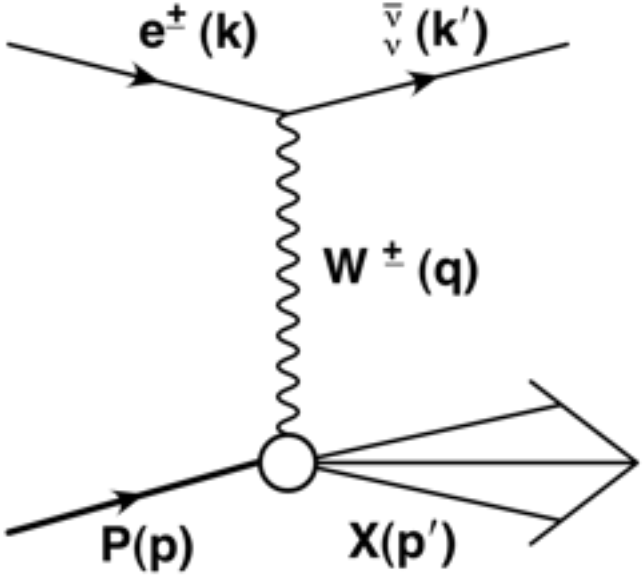
$$y = (q\cdot p)/(k\cdot p)$$



HERA overlaps with both fixed-target and Tevatron experiments

Neutral and charged current DIS processes





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

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

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

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

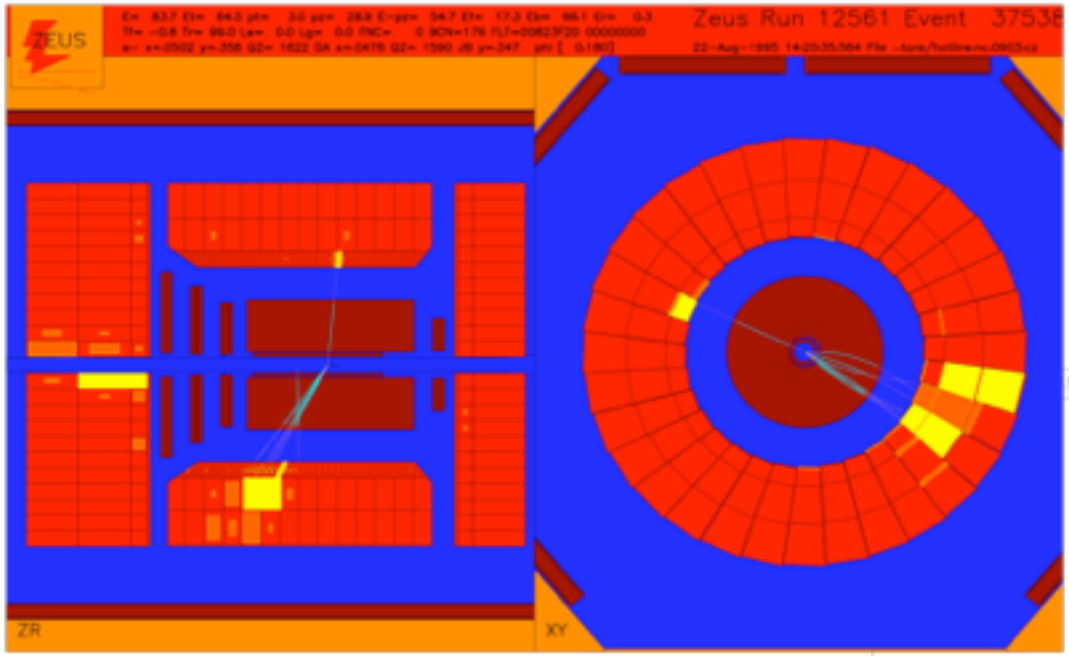
$F_L \sim$ gluon density

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

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

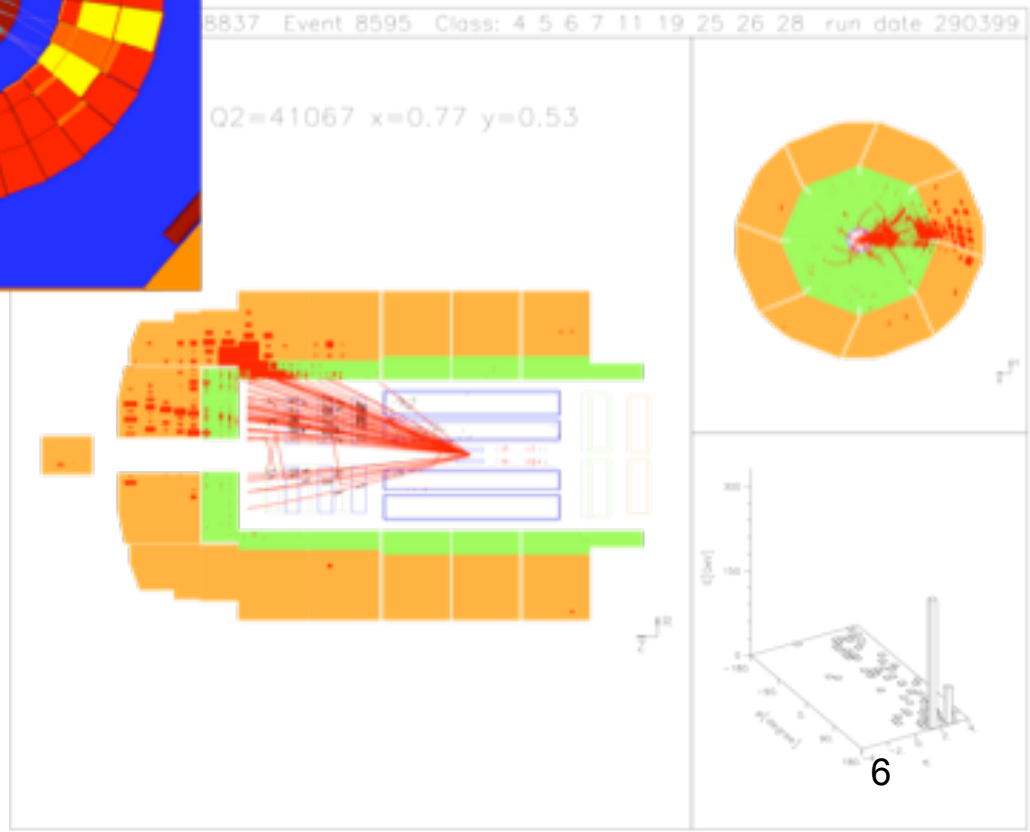
Sensitive to individual quark flavours

DIS events in H1 and ZEUS



Charge current :

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

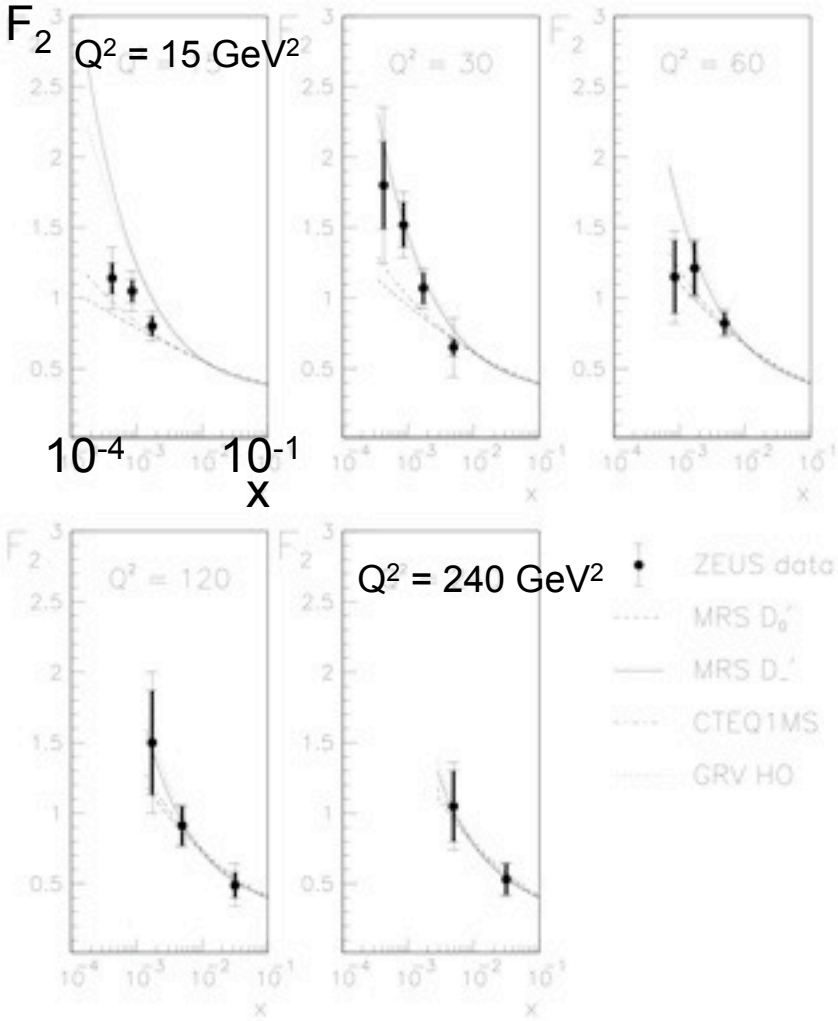


Neutral current :

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

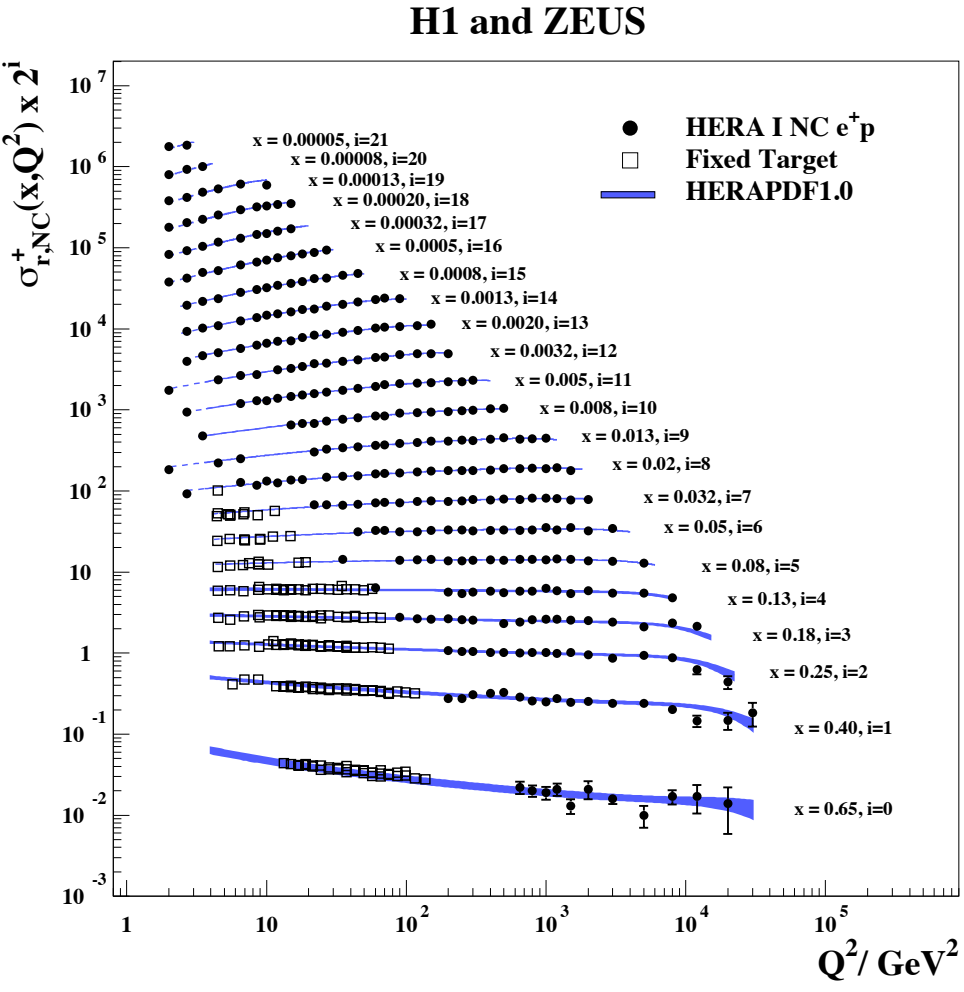
Early HERA measurements of F_2

- All early DIS experiments were fixed target experiments with *e, μ, ν* on various targets and at high *x*
- Using just a small amount of data, the first measurements of F_2 were made in 1993/4.
- Constitutes the major discovery of HERA :
  - The rise of the proton structure function with decreasing *x*.
  - Fixed-target data was too high in *x*; predictions varied.
  - Due to the rapid increase in the gluon density to low *x*.



Combined data

Combination of inclusive DIS



The physics :

- Strong rise of the cross section at low *x* due to large gluon density.
- High *x* dominated by valence quarks.
- Description by QCD works from a few *GeV*^{2} upwards.

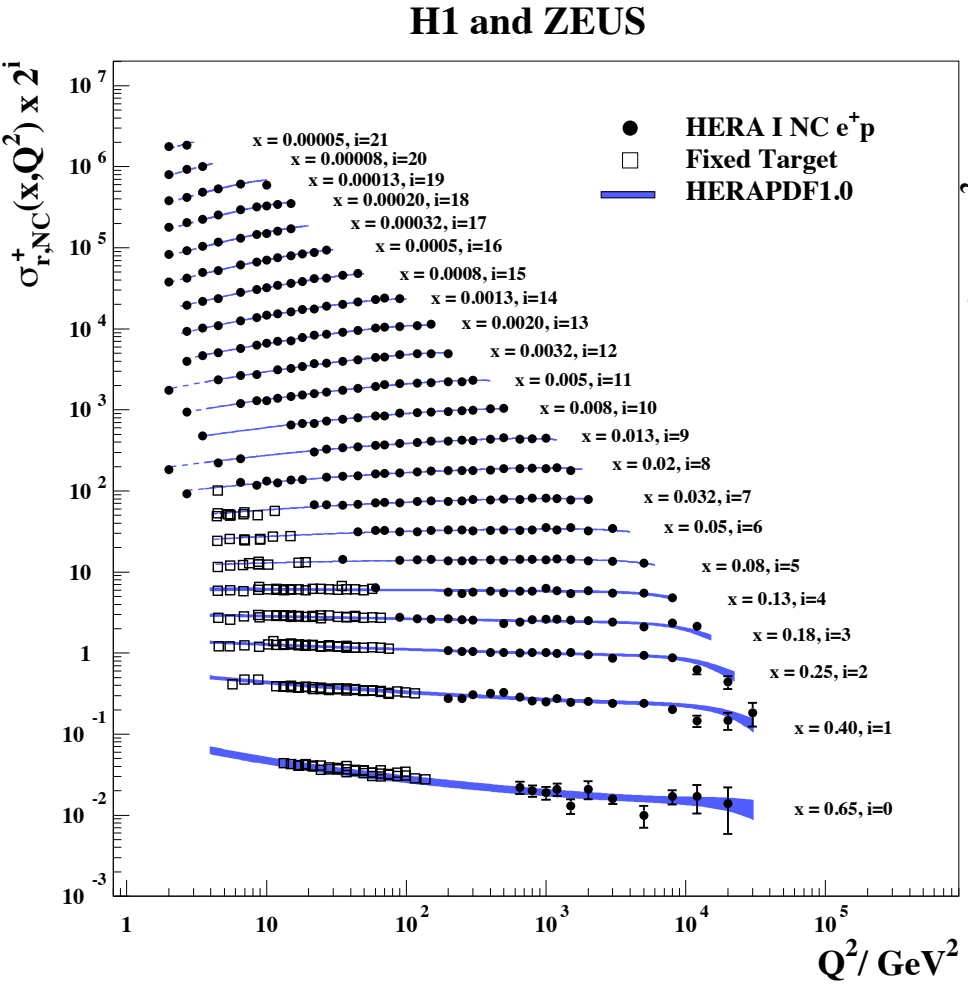
Combination of H1 and ZEUS data :

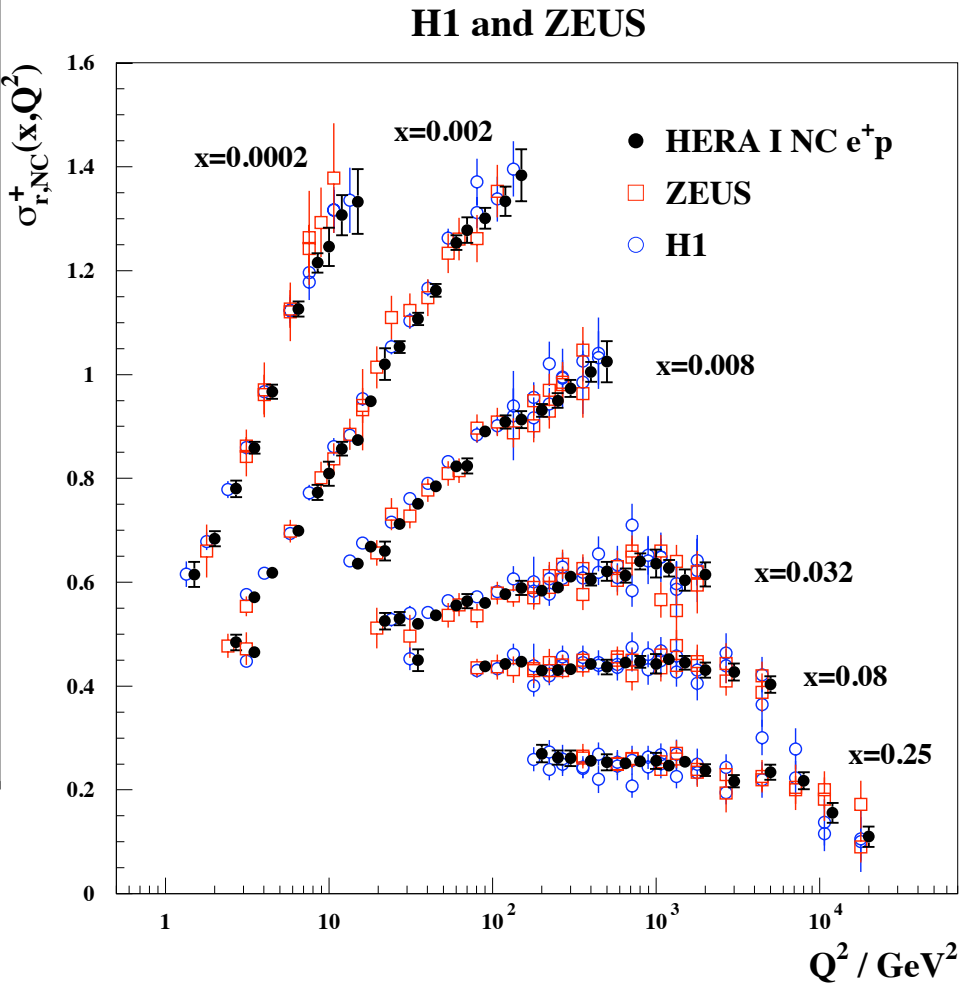
- About 1400 points combined;
- Many now of *O(1%)* precision;
- Correlation of systematic uncertainties taken into account.

- Tremendous experimental achievement and stunning success of QCD

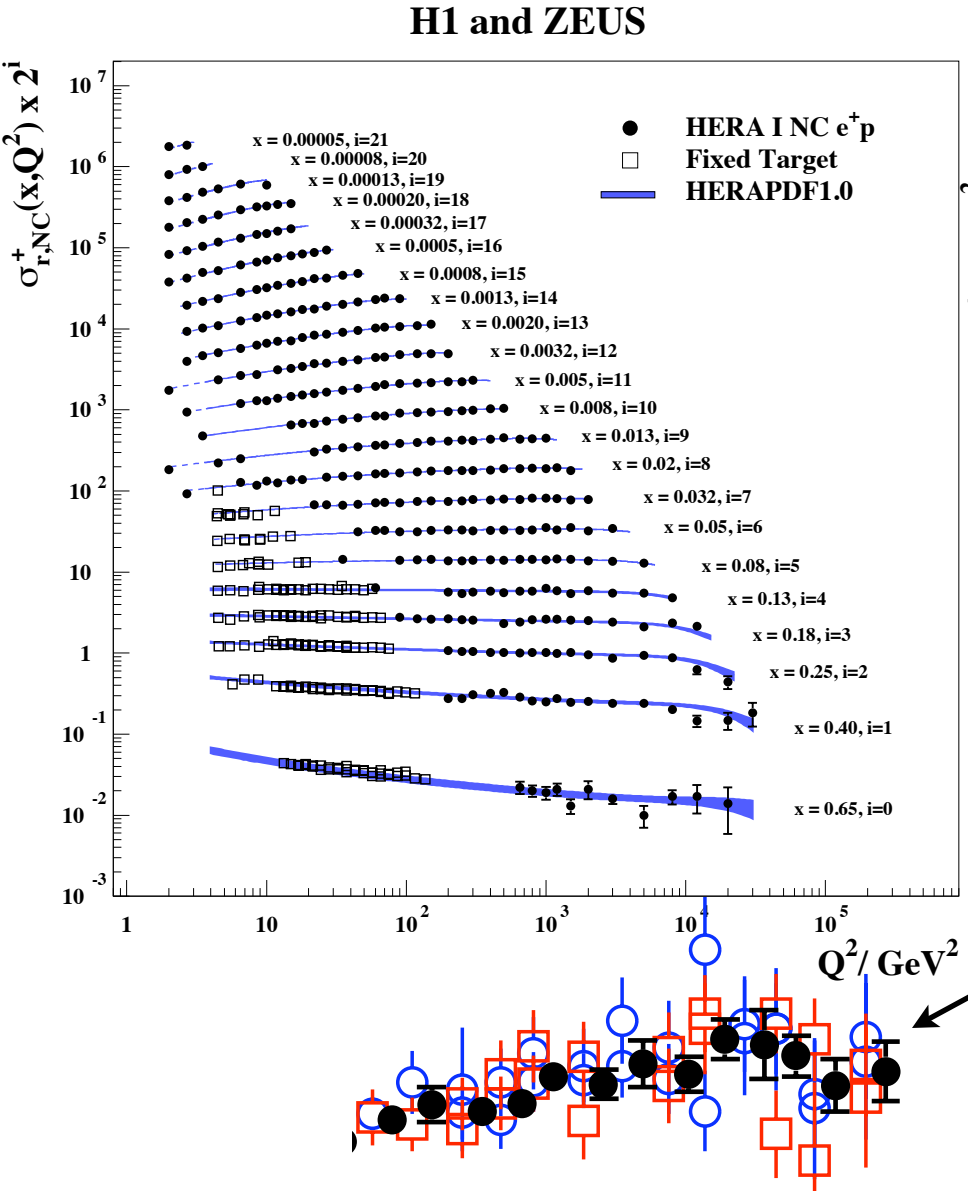
[JHEP 01 (2010) 109]

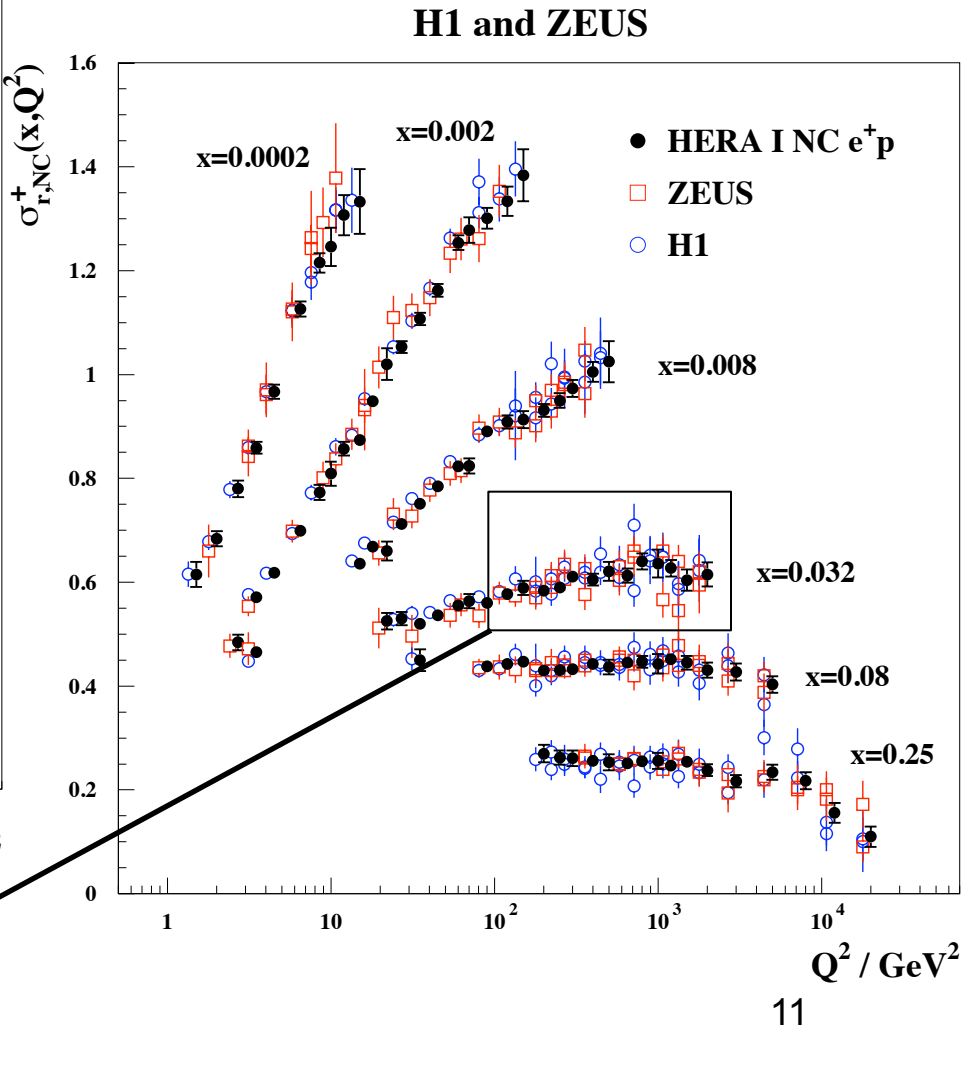
Combination of inclusive DIS



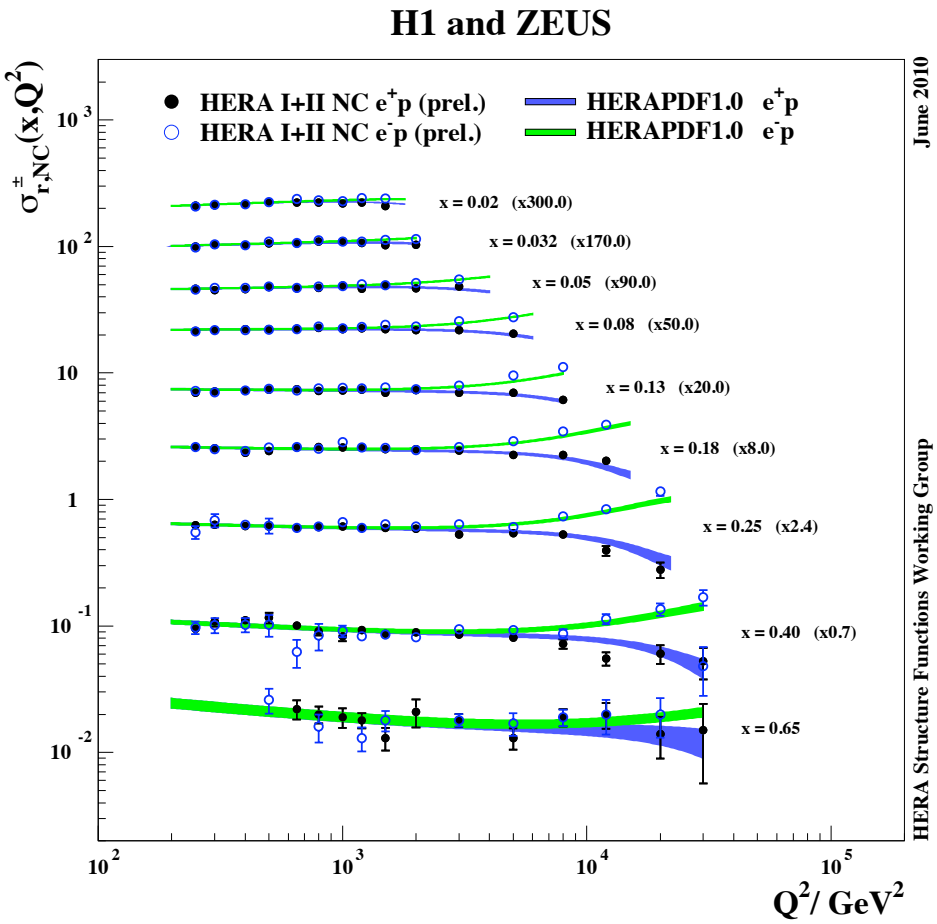


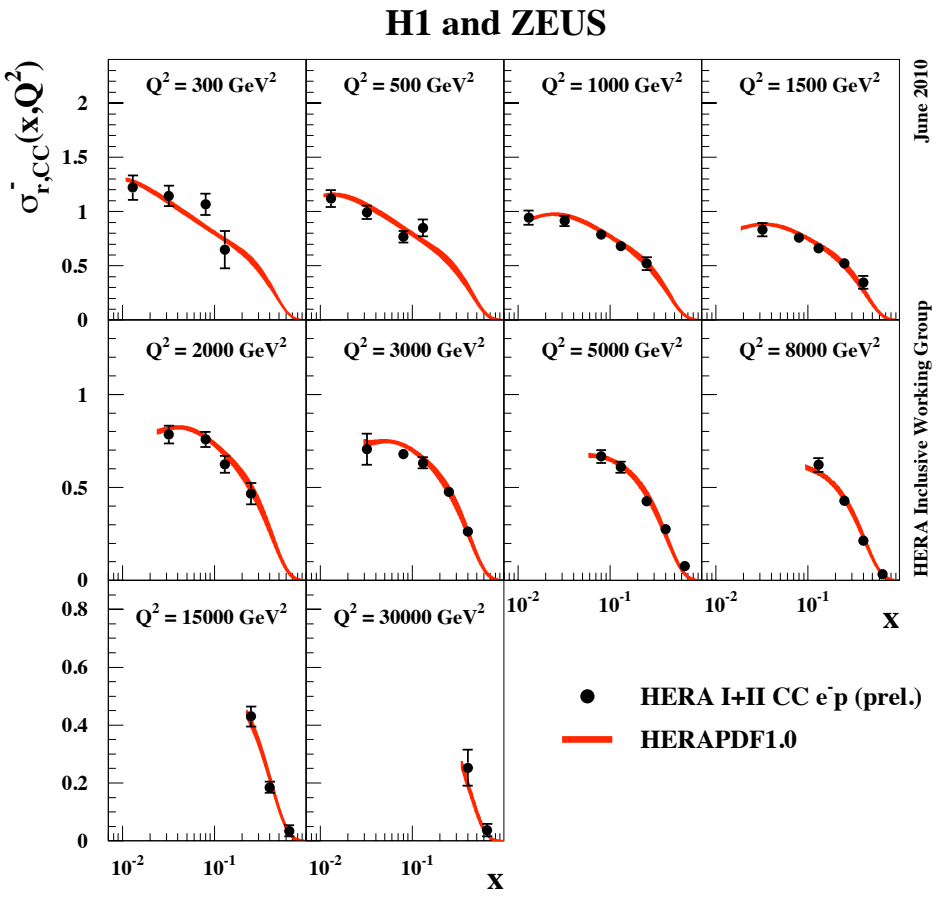
Combination of inclusive DIS





High Q^2 measurements

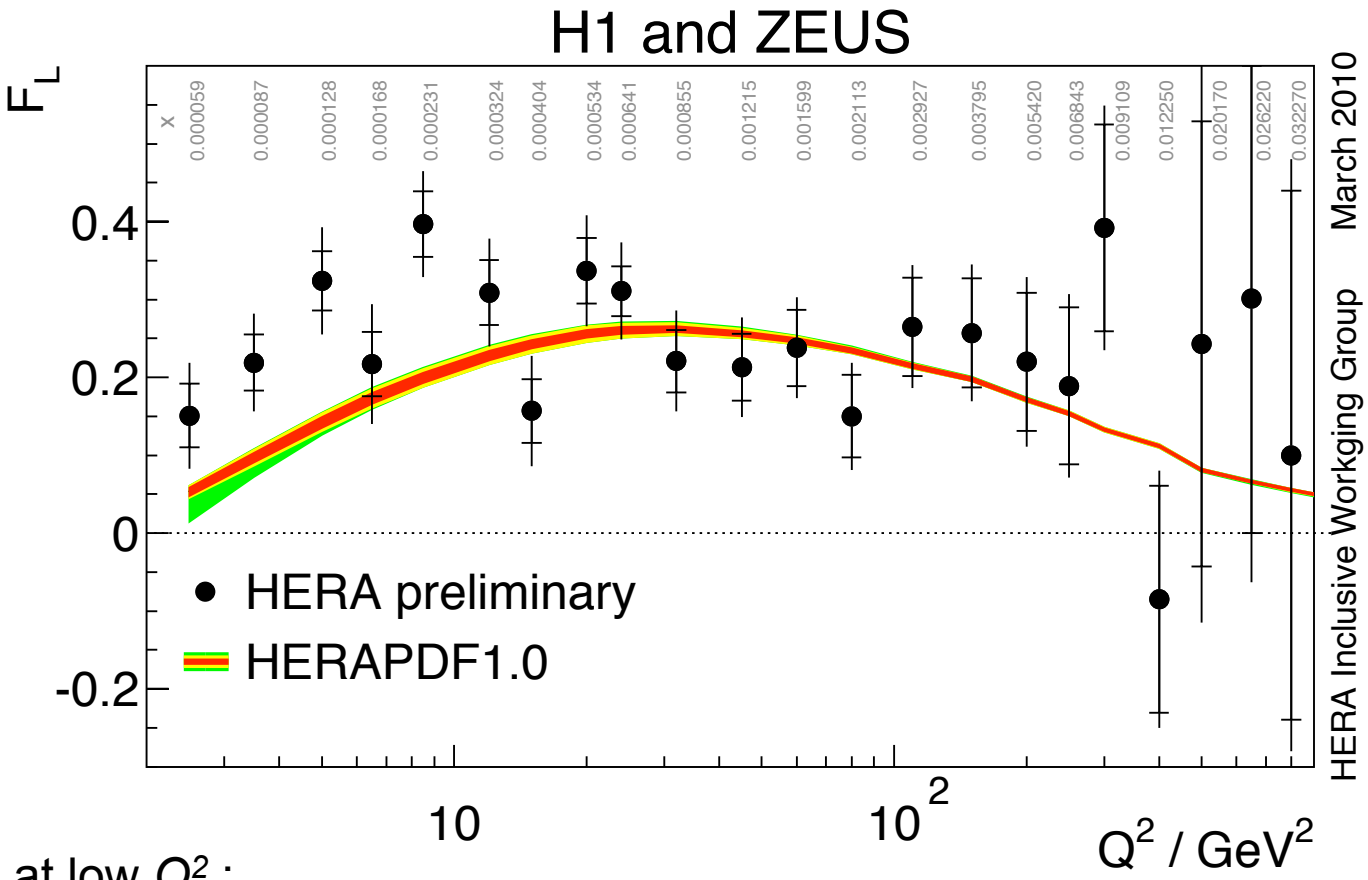




Data at higher Q^2 (NC / CC; *1 fb*$^{-1}$) being combined :

- Effect of xF_3 structure function clearly seen.
- Description of both NC and CC data by NLO QCD fit is good.
- Use in fits to improve in particular high x valence quarks.

Measurement of F_L



Extra data at low Q^2 :

- Vital measurement (using data at different E_p) to check the assumptions in QCD fits.
- Reasonable description by QCD fit; other QCD models constrained by these data.
- Charm (and bottom) data at low x and Q^2 also combined and used in QCD fits.

Combined PDF fit

Extraction of parton densities—HERAPDF

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

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

σ_{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, a series expansion in α_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..

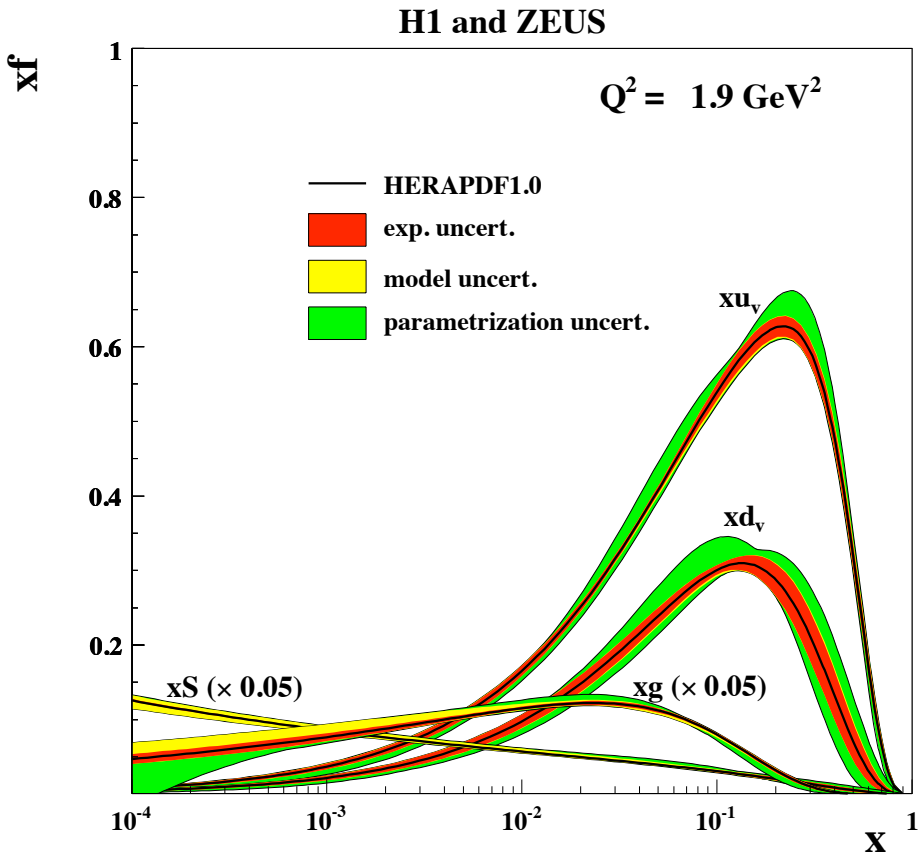
Data used :

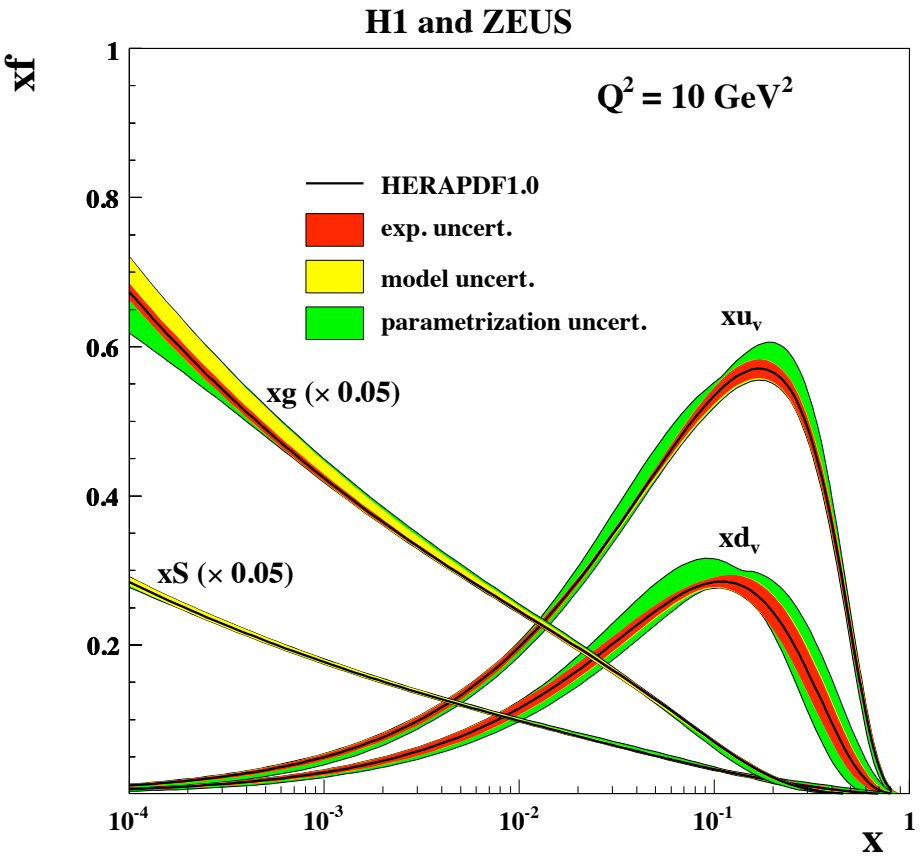
- HERAPDF1.0 : NC, CC ($Q^2 > 100\ GeV^2$); NC ($Q^2 > 0.045\ GeV^2$) [JHEP 01 (2010) 109]
- HERAPDF1.X : Low-E_p data ($Q^2 > 2.5\ GeV^2$); HERA II high Q^2 data; charm data [prel.]

Uncertainties :

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

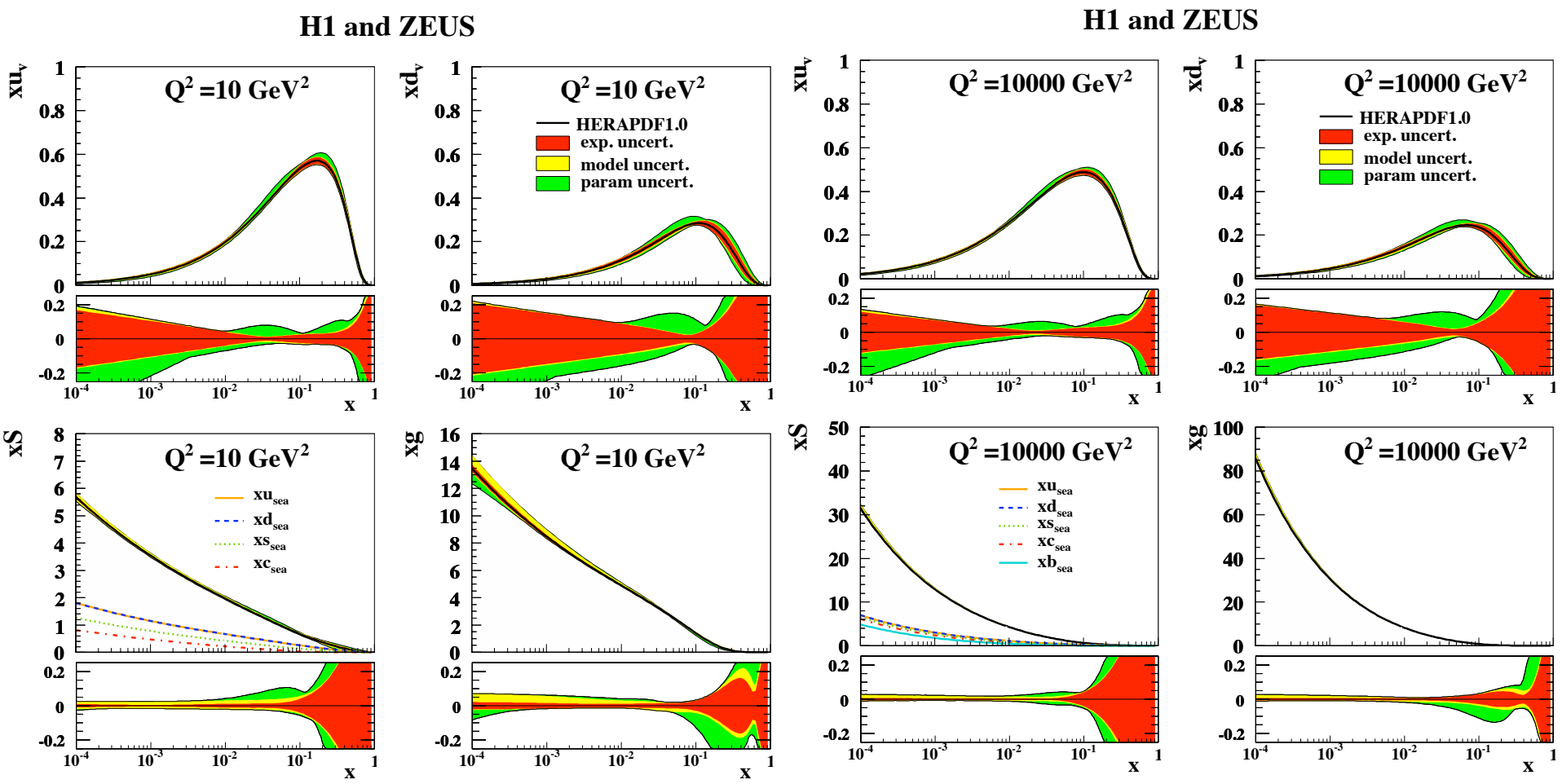
HERAPDF





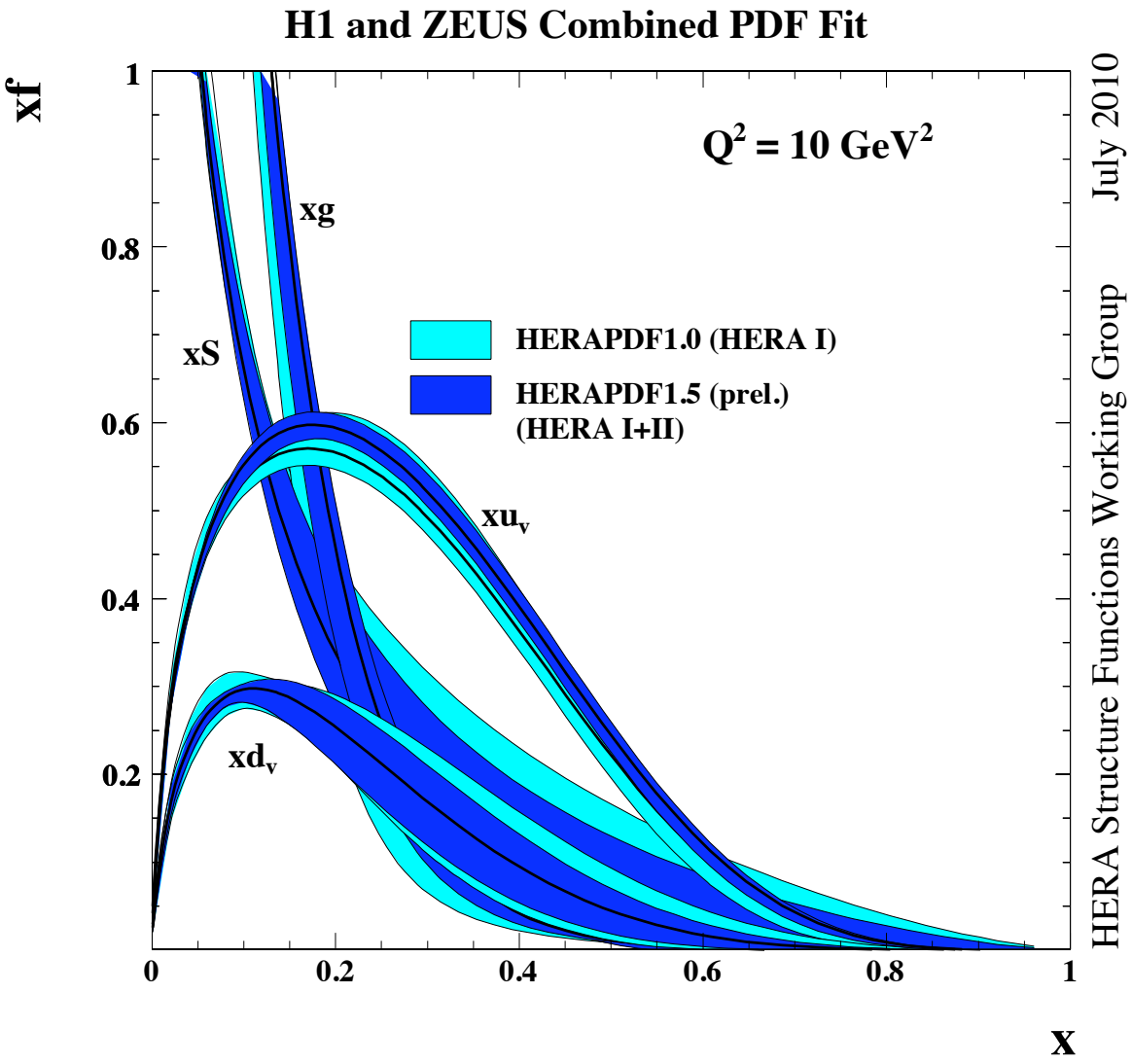
- Valence-like shape of gluon distribution at starting scale.
- Dominance of gluon distribution at low *x.*
- Precise at low *x* for gluon and sea distributions; parametrisation uncertainty dominates.

HERAPDF uncertainties



- E.g. uncertainty on *xg* at Q^2 = *10000 GeV*^{2} and *x < 0.01* is *2 %*
- HERAPDF1.0 set in LHAPDF v5.8.1

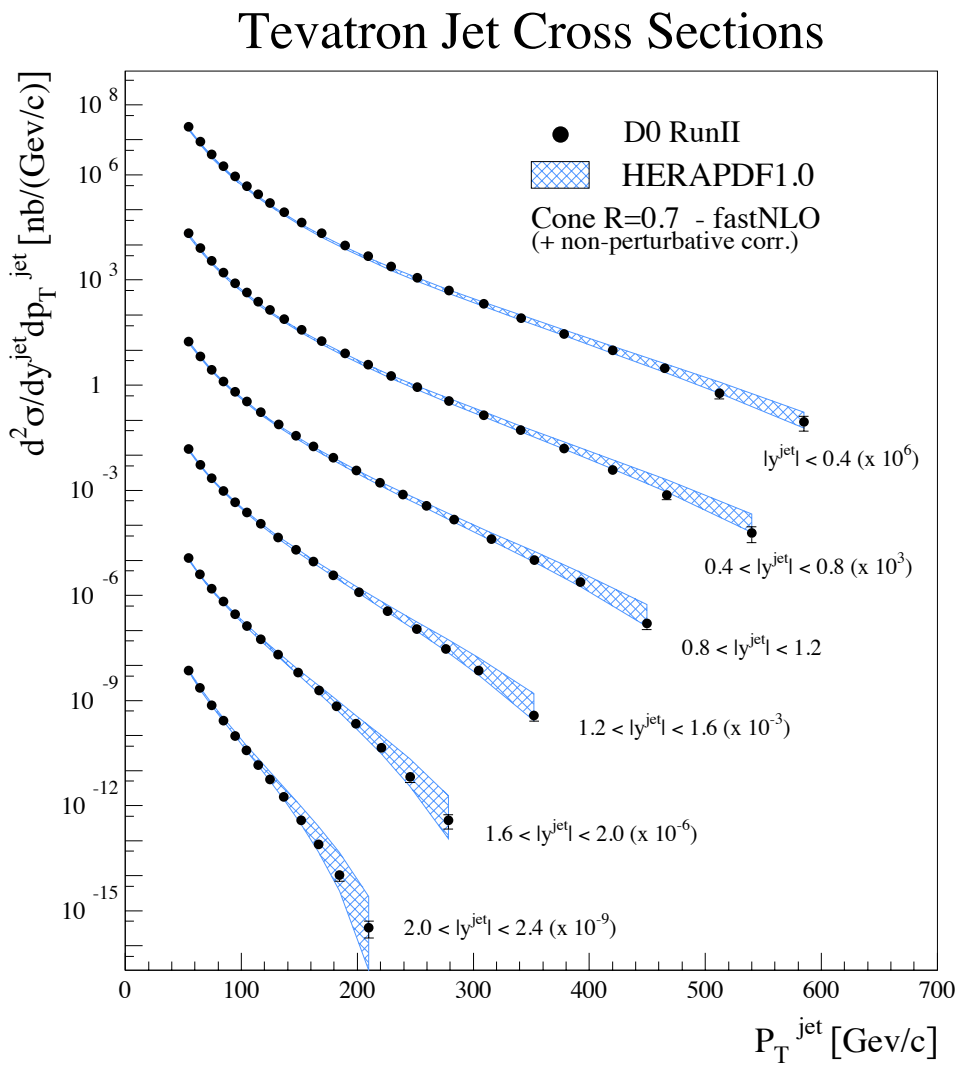
HERAPDF1.0 vs HERAPDF1.5

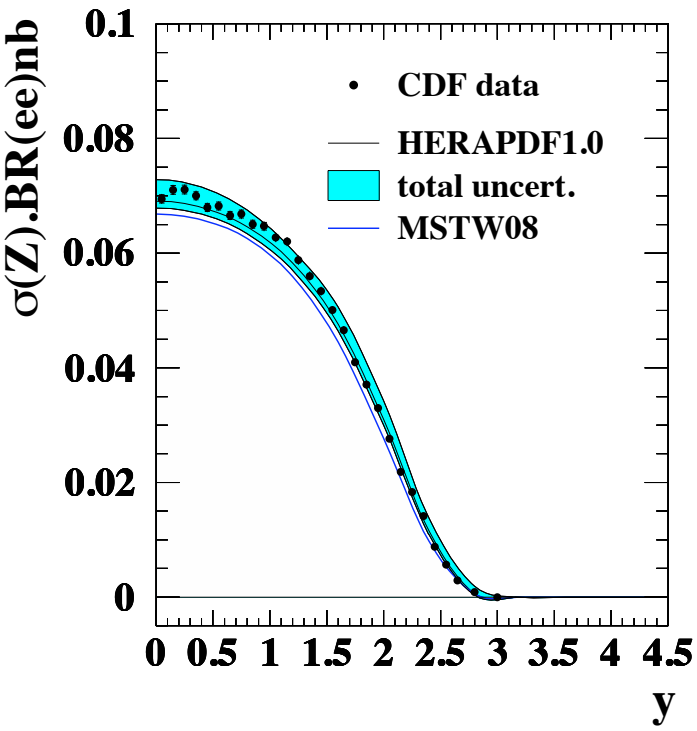


- Settings same in both versions
- Experimental and parametrisation uncertainty reduced.
- As hoped, uncertainties reduced :
  - at high x
  - in valence distributions

Other colliders and PDFs

HERAPDF compared to Tevatron data

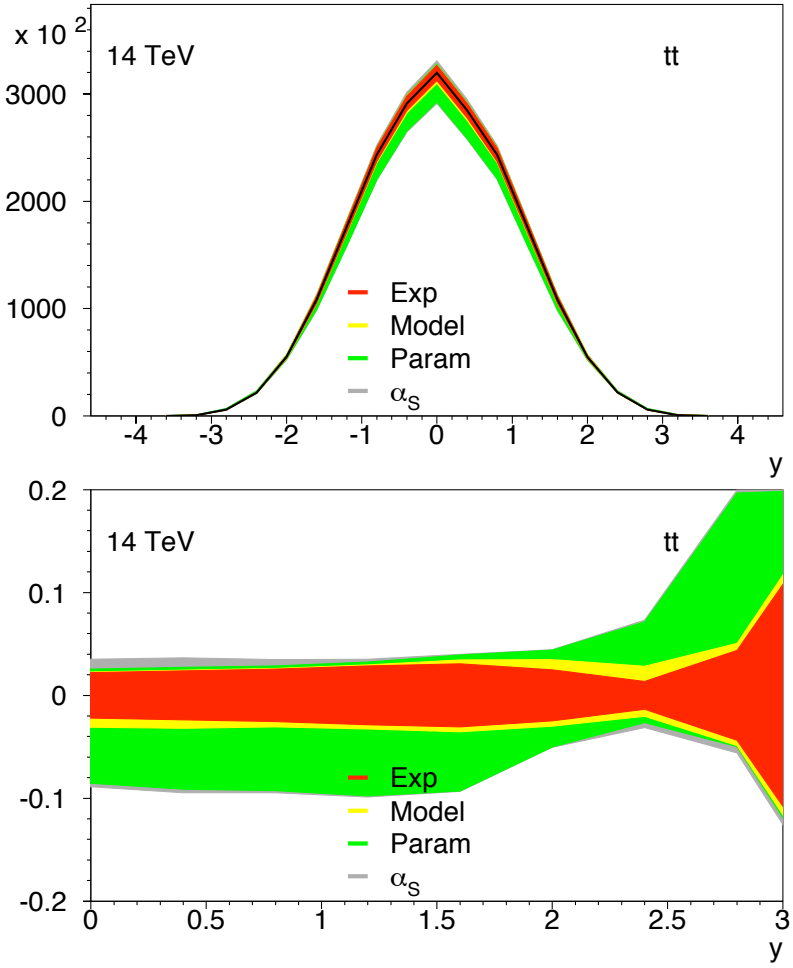




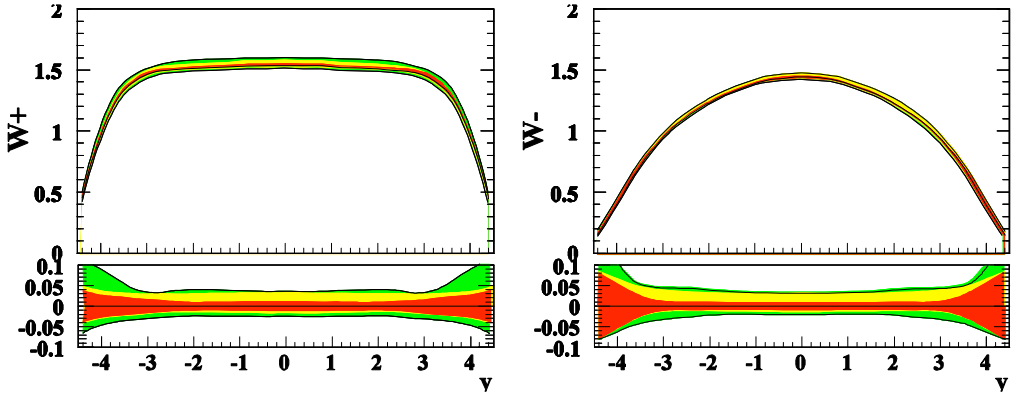
- Jet, Z (and W) production at the Tevatron well described by HERAPDF.
- Can / should be used to compare all measurements in proton collisions.

HERAPDF predictions for the LHC

$t\bar{t}$ production at the LHC :

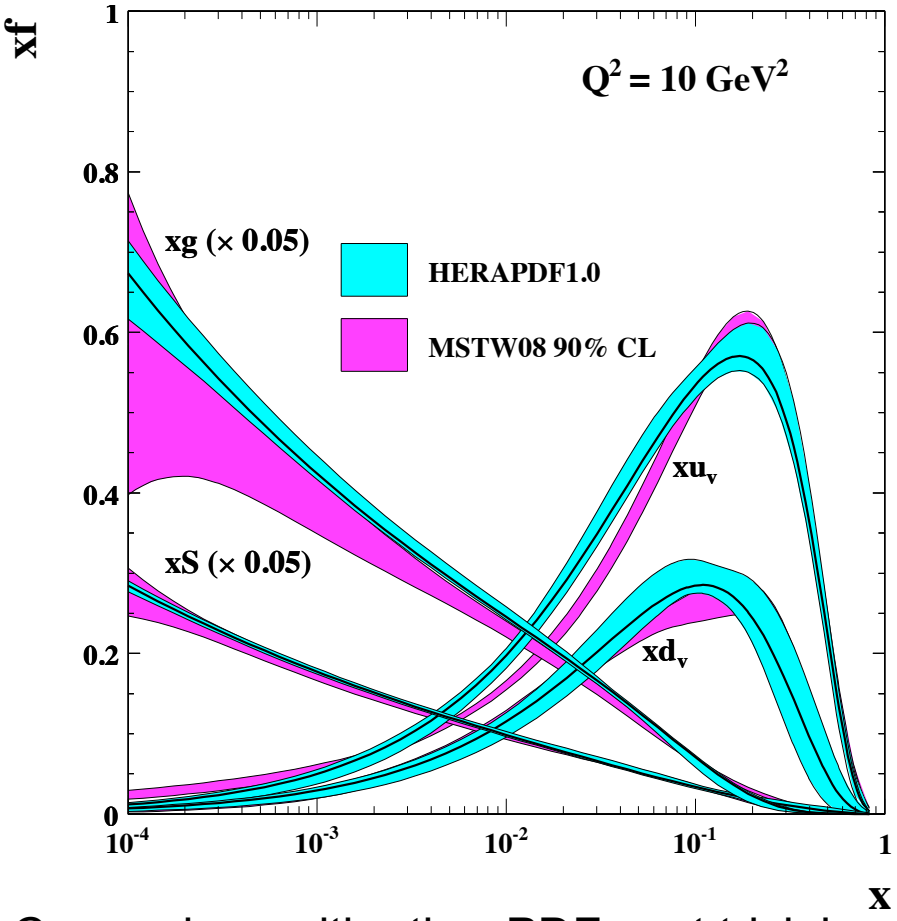


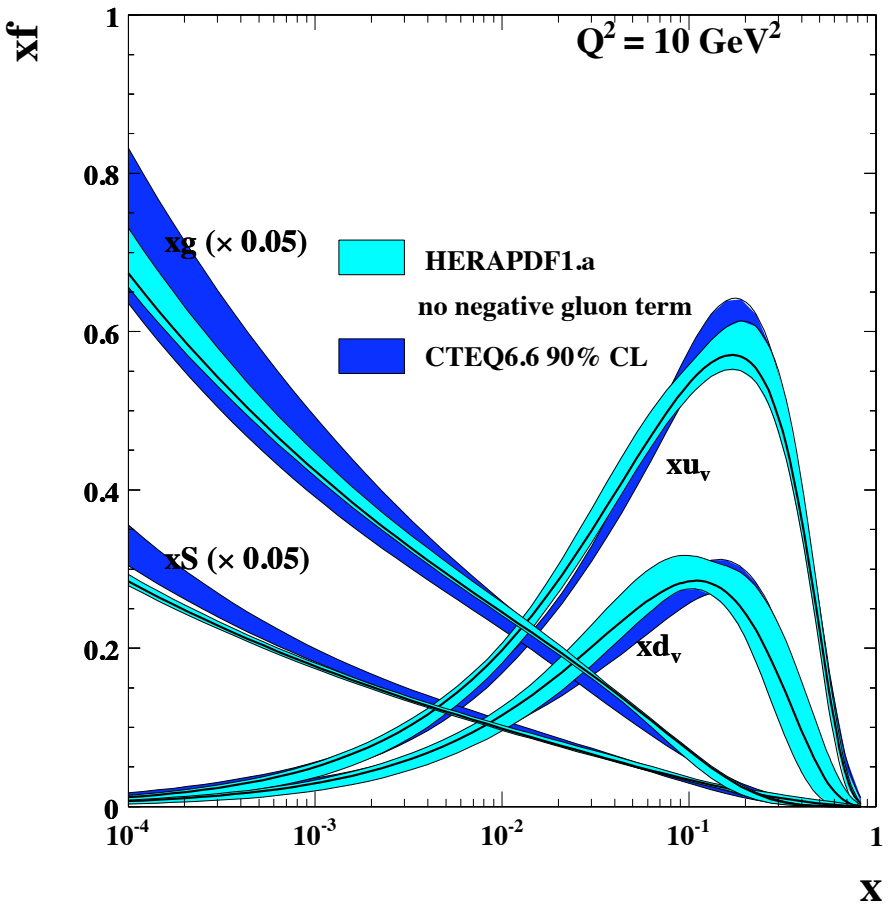
W (and *Z*) production at the LHC :



- W / Z production could be a luminosity measure; uncertainty is ~5% in central region.
- Several cross sections at different energies at the LHC have been calculated.
- Ready to be compared to data.

Comparison with other PDFs



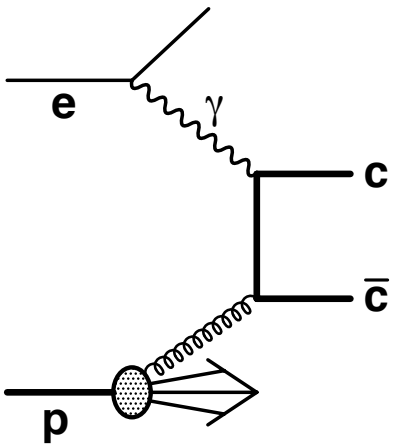


Comparison with other PDFs not trivial :

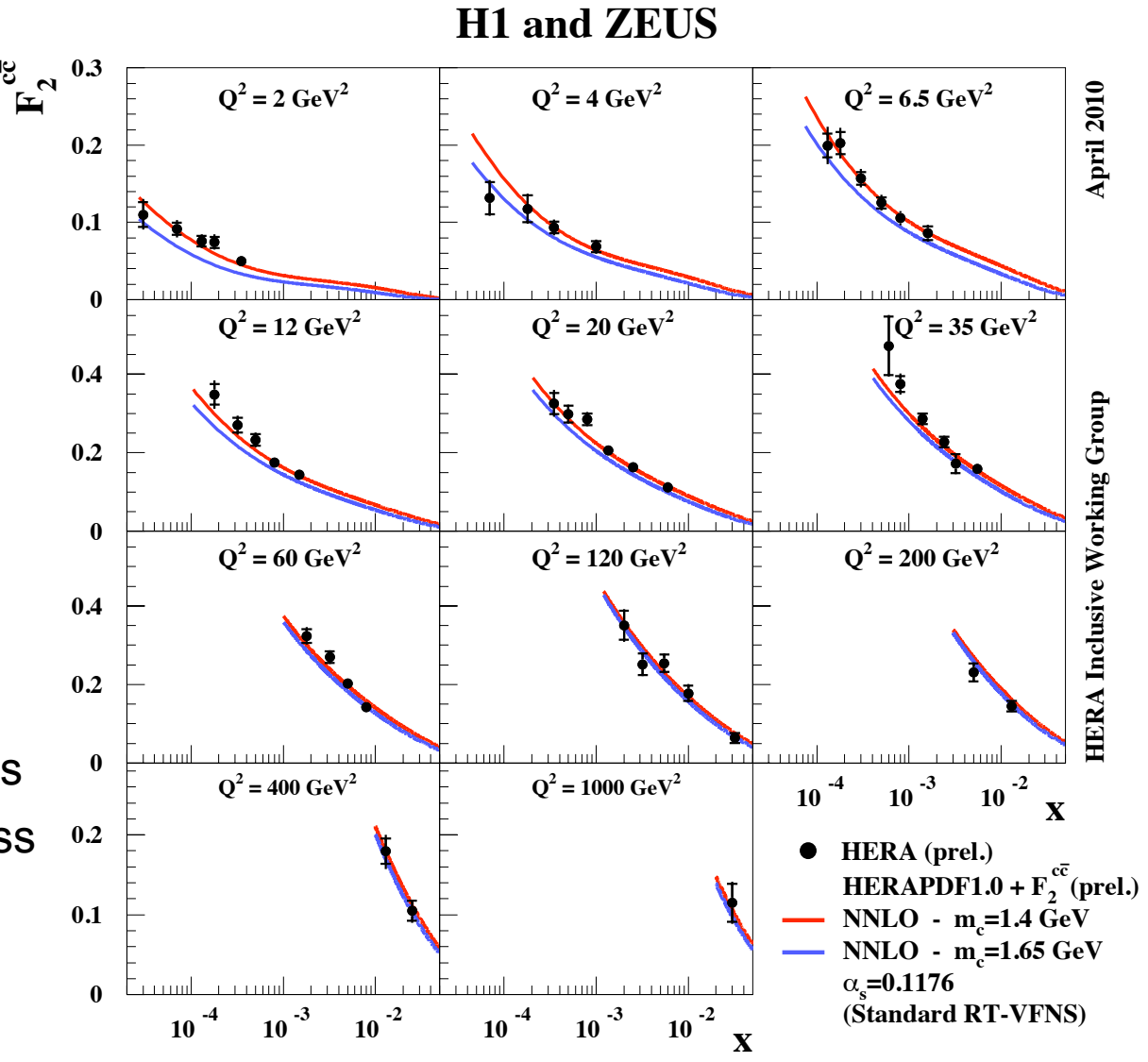
- HERAPDF uses combined data and MSTW (CTEQ) did not
- Different error treatment, model assumptions
- Consider all when making a measurement

Charm and NNLO

- Charm contribution to the proton structure well described



- Verification of gluon density extracted from scaling variations
- Sensitivity to heavy quark mass and scheme
- HERAPDF “approximated” NNLO

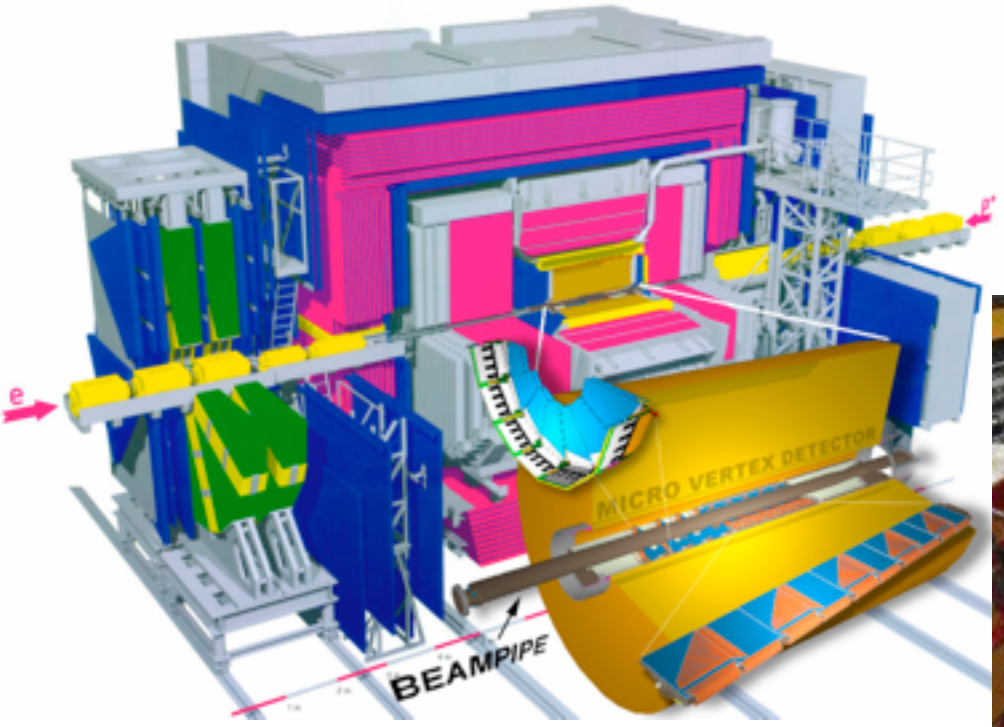


Discussion and summary

- Combination of H1 and ZEUS data has led to significant improvement in precision over an individual experiment which is reflected in HERAPDFs.
- Each new HERAPDF release uses previously unavailable, more precise data.
- Input H1 and ZEUS data to HERAPDF is well understood with no tension and covers a vast kinematic region.
- The measurements do not suffer from residual ambiguities such as nuclear corrections or strong isospin assumptions in the fit (e.g. $u_n = d_p$).
- Full uncertainties available along with central predictions for HERAPDF1.0 in LHAPDF.
- HERAPDF1.0 should be used as standard in comparison to Tevatron / LHC measurements along with global fits such as CTEQ and MSTW.

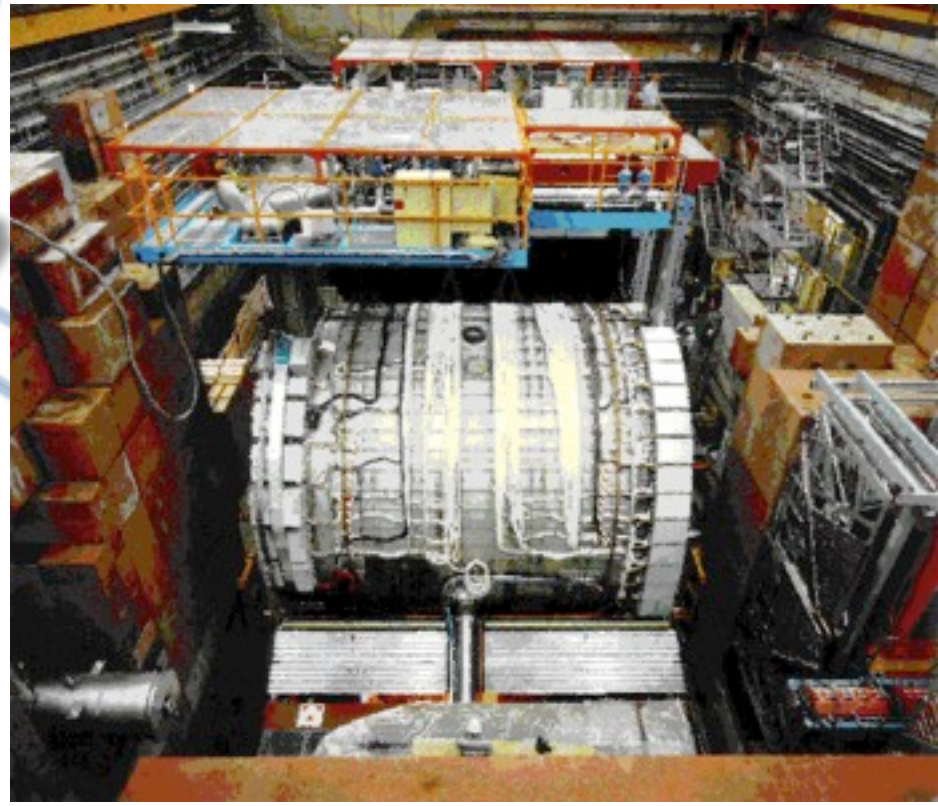
Back-up

The H1 and ZEUS detectors



Both large general-purpose detectors:

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



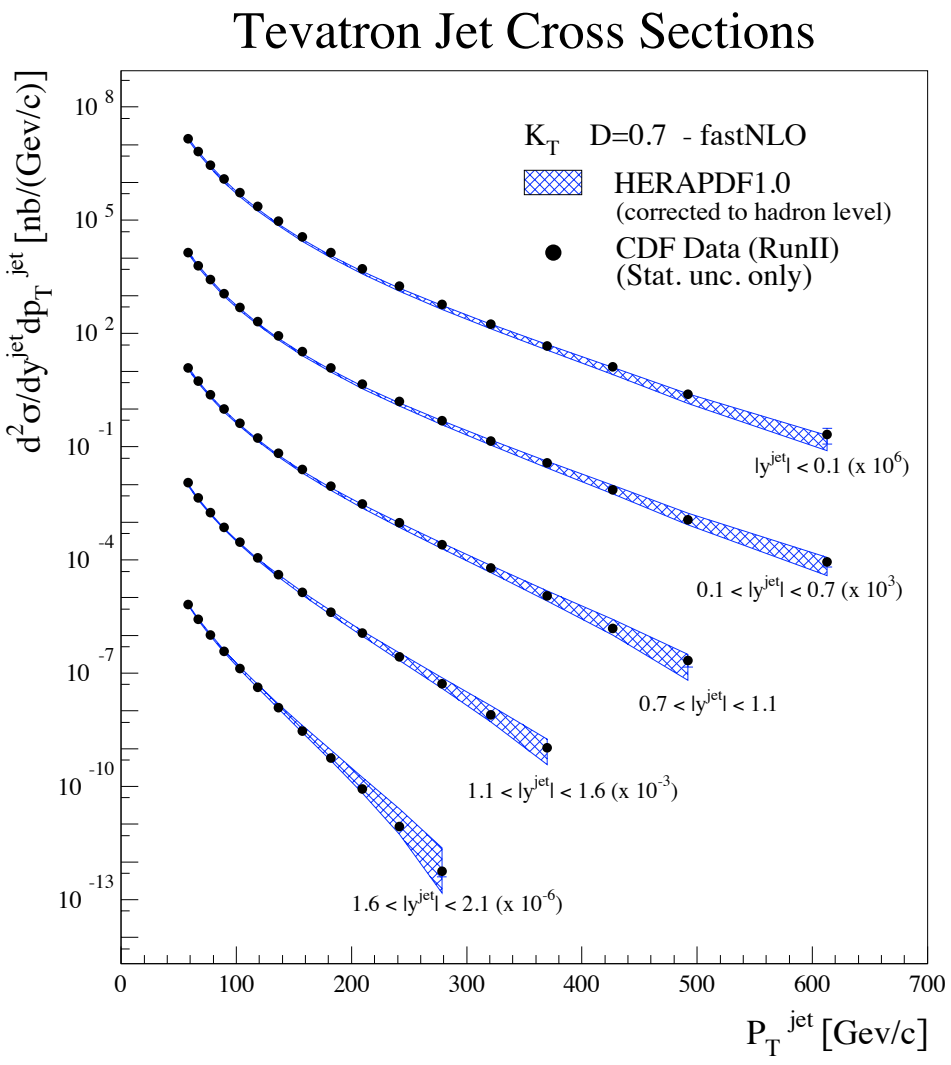
Sub-detectors consist of:

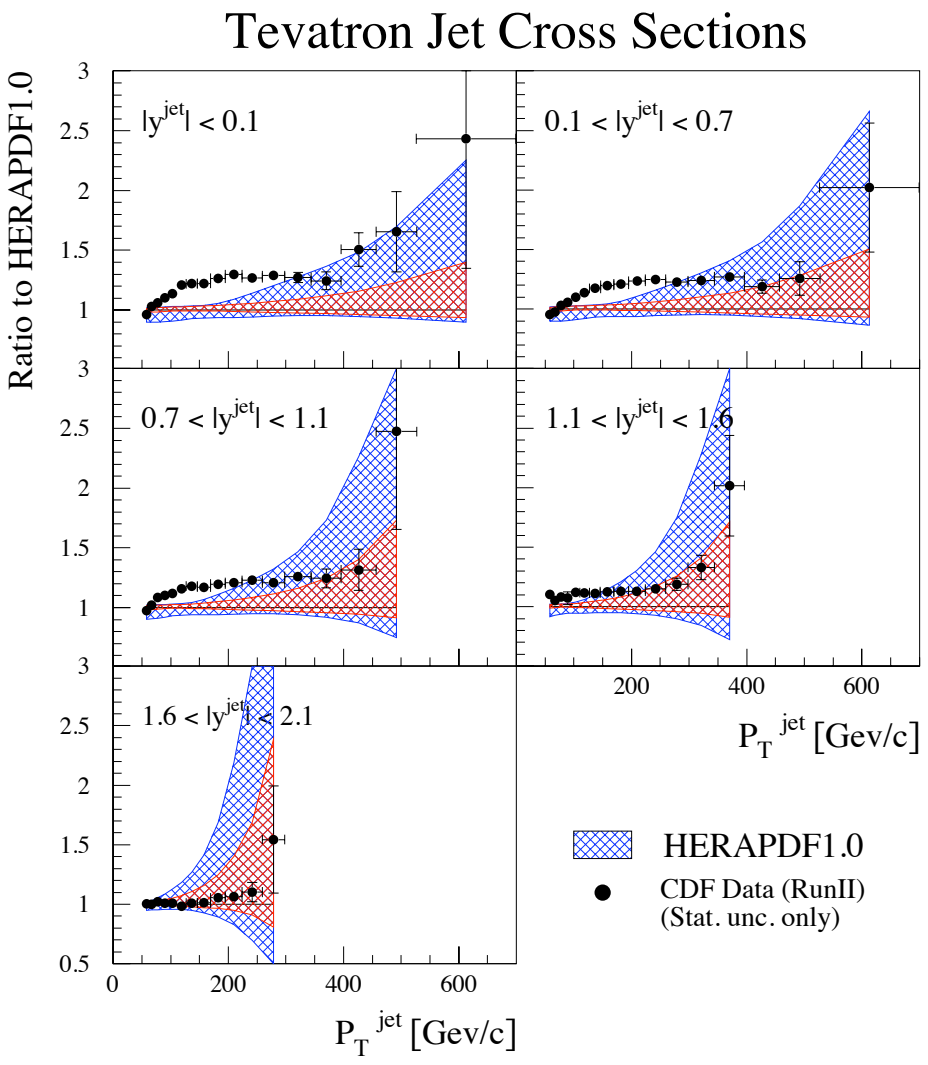
- Electromagnetic and hadronic calorimeters
- Tracking detectors
- Micro-vertex detectors
- Luminosity monitors
- Muon chambers
- …

Data combination

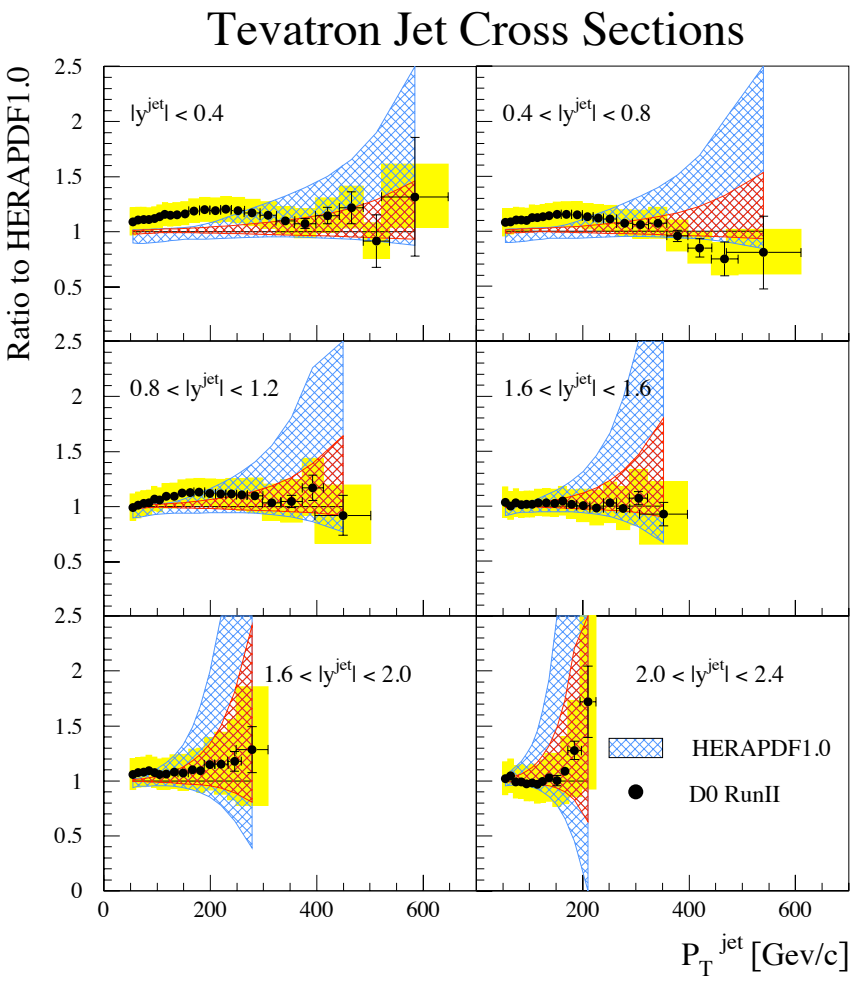
- Combination of H1 and ZEUS data gives ultimate precision
- Performed before QCD analysis and extraction of HERAPDF
- Data combination done [JHEP 01 (2010) 109] :
  - using a χ^2 minimisation procedure; $\chi^2 = 637/656$
  - 1402 individual measurements combined to 741 unique points with 113 sources of correlated systematic uncertainties
  - H1 and ZEUS had similar data samples $\rightarrow \sqrt{2}$ improvement in statistical precision
  - Some significant reduction in systematic uncertainties : different detectors and analysis techniques; different sensitivities to similar sources.

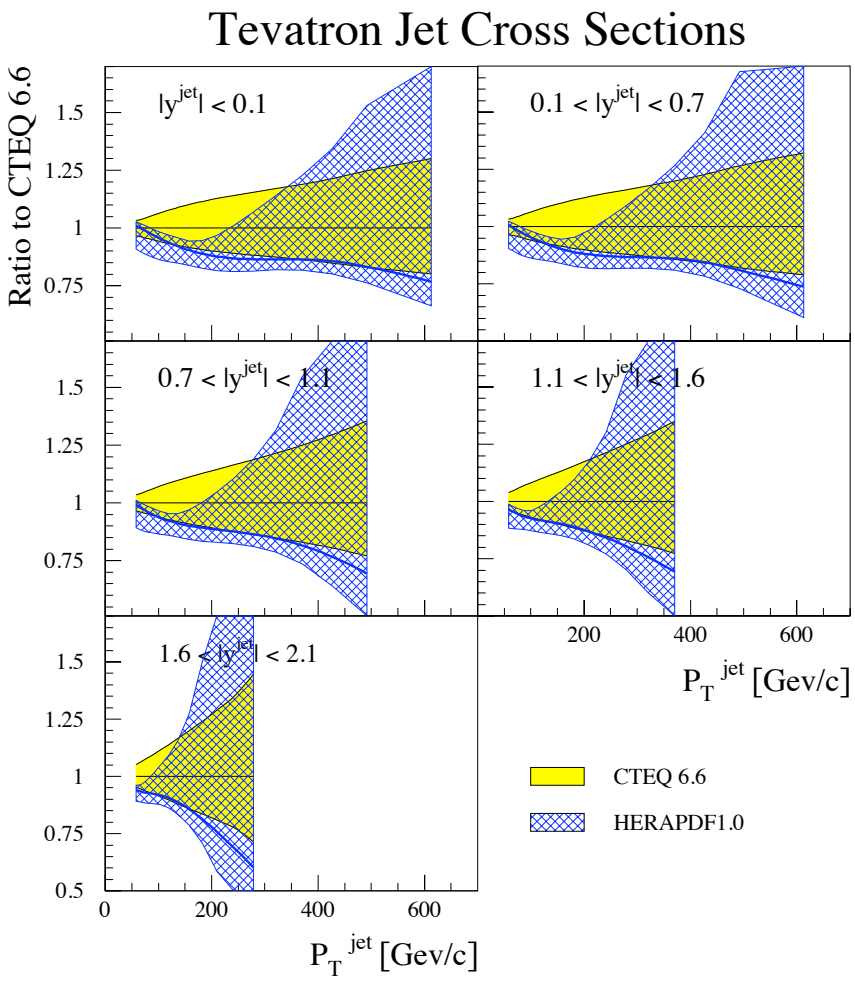
Tevatron data



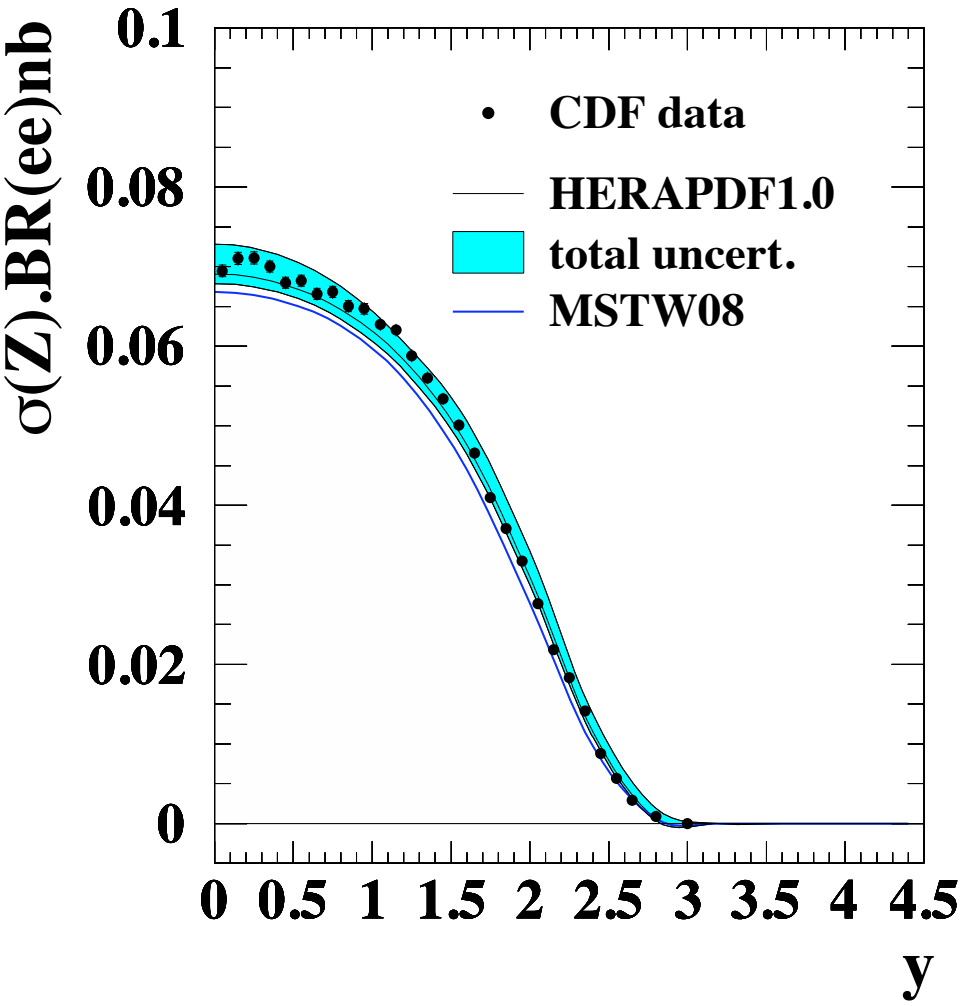


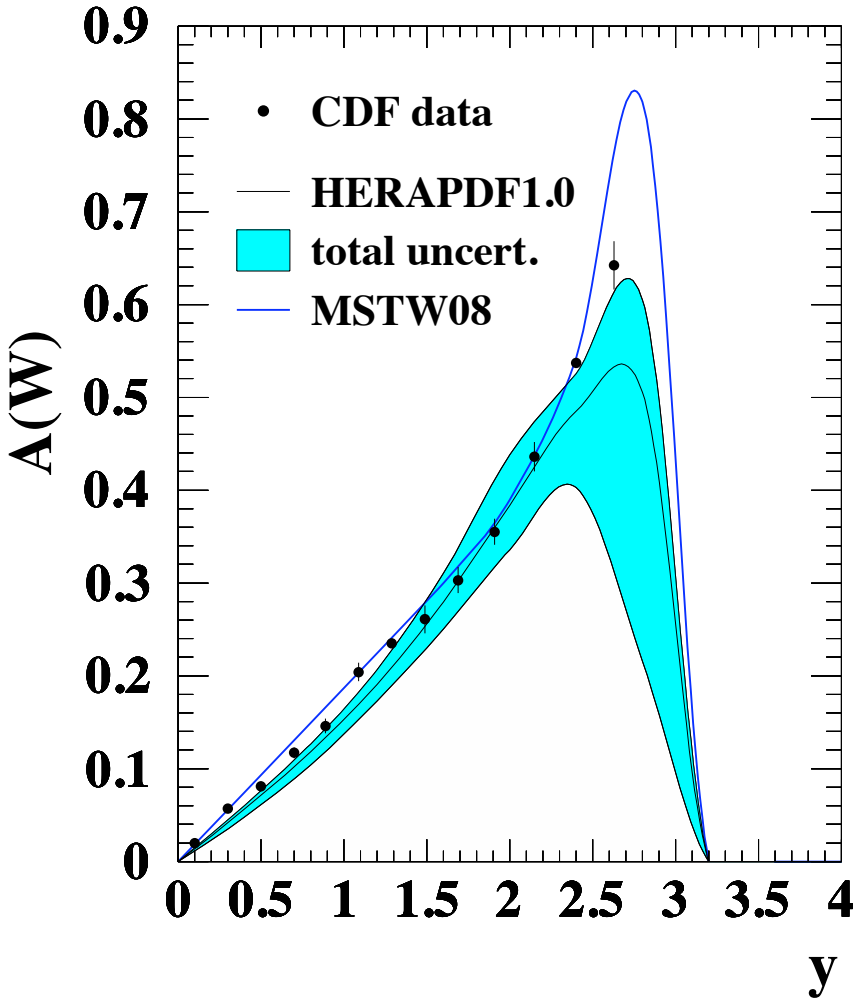
Tevatron


Tevatron Jet Cross Sections
Ratio to HERAPDF1.0
|y^jet| < 0.4
0.4 < |y^jet| < 0.8
0.8 < |y^jet| < 1.2
1.6 < |y^jet| < 1.6
1.6 < |y^jet| < 2.0
2.0 < |y^jet| < 2.4
HERAPDF1.0
D0 RunII
P_T^jet [Gev/c]


Tevatron Jet Cross Sections
Ratio to CTEQ 6.6
|y^jet| < 0.1
0.1 < |y^jet| < 0.7
0.7 < |y^jet| < 1.1
1.1 < |y^jet| < 1.6
1.6 < |y^jet| < 2.1
CTEQ 6.6
HERAPDF1.0
P_T^jet [Gev/c]

Tevatron data





Details of HERAPDF fit

- RT-VFNS (as for MSTW08) and investigated RT (optimal), ACOT (full and χ), FFNS
- PDF parametrised at the starting scale Q_0^2 : G, u_{val}, d_{val}, $\overline{U} = \overline{u} + \overline{c}$, $\overline{D} = \overline{d} + \overline{s} + \overline{b}$

$$xf(x,Q_0^2) = A\,x^B\,(1-x)^C\,(1 + \varepsilon\sqrt{x} + Dx + Ex^2)$$

- Apply quark number and momentum sum rules
- Optimum number of parameters chosen by saturation of χ^2 : central fit with 10 free parameters; $\chi^2/dof = 574/582$

Scheme	TRVFNS
Evolution	QCDNUM17.02
Order	NLO
Q_0^2	$1.9\ GeV^2$
$f_s = s/D$	0.31
μ_R	Q^2
μ_F	Q^2
Q_{min}^2	$3.5\ GeV^2$
$\alpha_S(M_Z)$	0.1176
M_c	1.4 GeV
M_b	4.75 GeV

- Uncertainties :
  - $\Delta\chi^2 = 1$
  - Model uncertainties

Variation	Standard Value	Lower Limit	Upper Limit
fs	0.31	0.23	0.38
Mc (GeV)	1.4	1.35	1.65
Mb (GeV)	4.75	4.3	5.0
Q_{min}^2	3.5	2.5	5.0
Q_0^2	1.9	1.5	2.5

- Parametrisation uncertainties : envelope of PDF uncertainties with variation of Q_0^2 and envelope of variation of parameters.

Impact of combined data in CTEQ PDFs