HERA data & Precision Partons for the LHC

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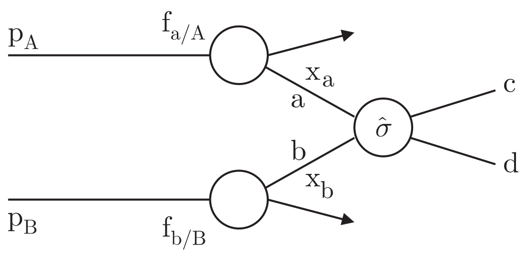
For the H1 and ZEUS Collaborations

- Introduction
- Combined deep inelastic data
- NLO QCD fit to the combined data
- Implications for LHC measurements
- Outlook

LHC - pp collisions at 14 TeV

• Quarks and gluons (partons) cannot be isolated and collided , protons are the most cost-effective particle to accelerate.

• For calculation of a hard process proton parton momentum density functions (PDFs) are required.



- Hard hadronic process $AB \rightarrow cdX$

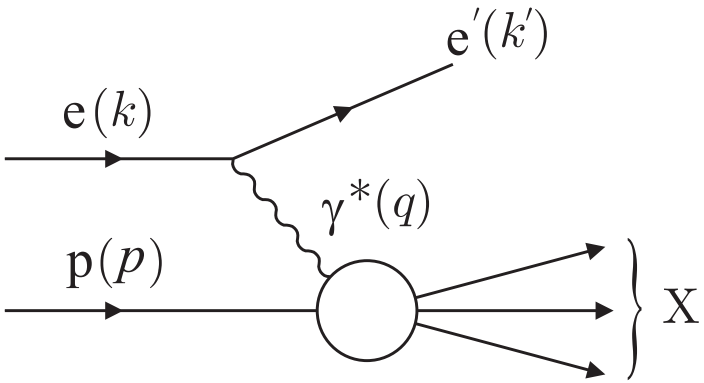
$$\sigma_{\text{hard}}(AB \rightarrow cdX) = \sum_{a,b} \int_0^1 dx_a dx_b \, f_{a/A}(x_a, \mu^2) f_{b/B}(x_b, \mu^2) \hat{\sigma}(ab \rightarrow cd, \mu^2)$$

- $f_{a/A}$ momentum density function for parton a in hadron A with fraction x_a of the hadron momentum p_A, universal functions, but have to be measured
- μ the hard scale, e.g. jet E_T, lepton pair invariant mass

Deep Inelastic scattering

One very powerful way of experimentally investigating the strongly interacting particles (hadrons) is to look at them, to probe them with a known particle; in particular the photon.

Richard Feynman *Photon-Hadron Interactions* Benjamin 1972



- incoming electron radiates a photon

  $q = k - k'$

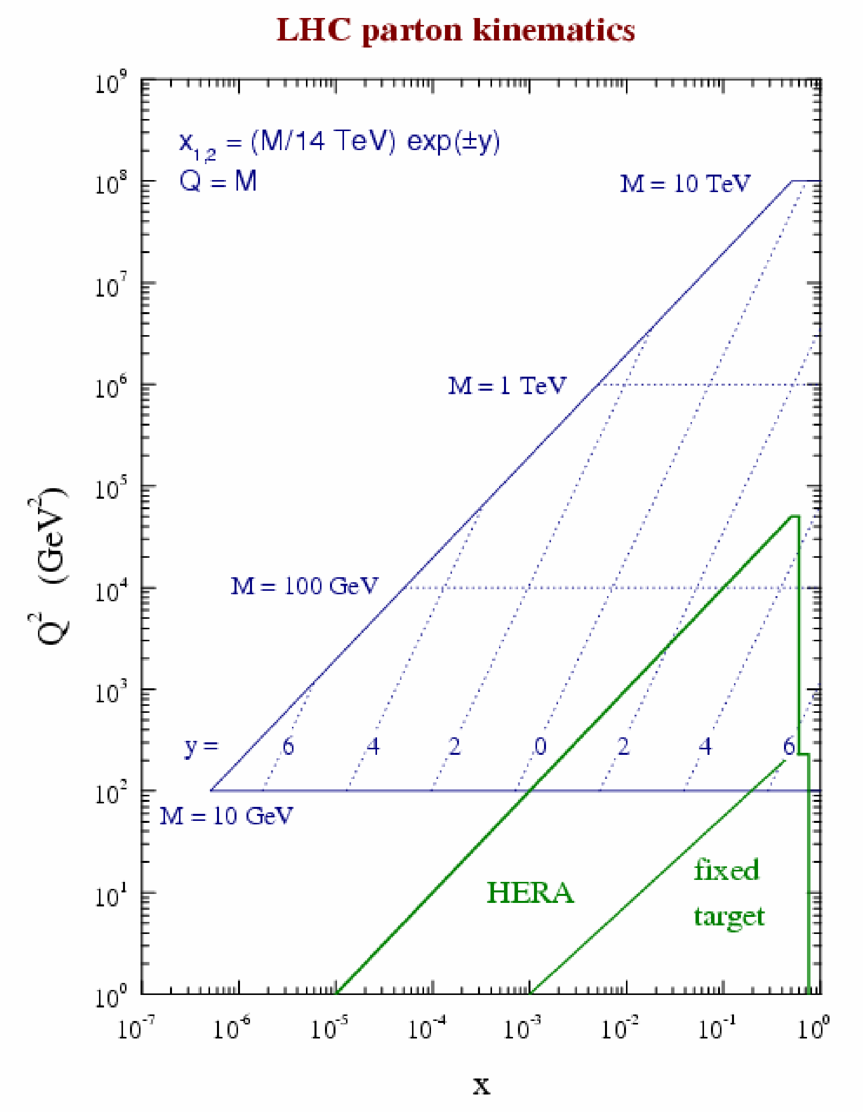
  $Q^2 = -(k - k')^2$ virtuality of the probe

- At HERA,

  $e^{\pm} p \rightarrow e^{\pm} X$ neutral current (NC: γ^*, Z^0)

  $e^{\pm} p \rightarrow \bar{\nu}(\nu) X$ charged current (CC: $W^{\pm}$)

LHC kinematic region – x vs $(Q=M)^2$

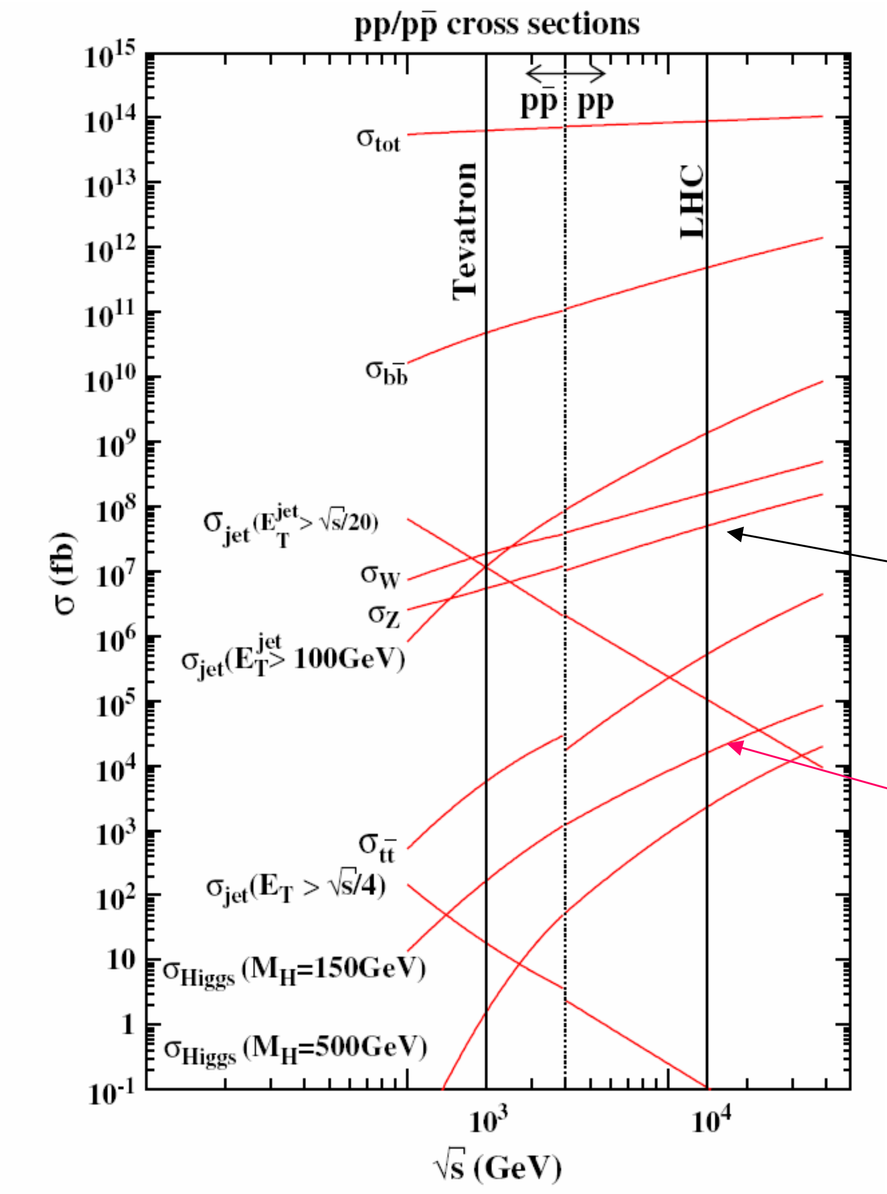


HERA has covered the region in x need for exploration of mass scales around 100 GeV and above at the LHC

Kinematics of deep-inelastic scattering restricts the physical region – note the strong correlation between Q^2 and x

Q^2 and x can be reconstructed from known or measured momenta

Why precision matters



Plot shows p$\bar{p}$ and pp cross-sections

vs $\sqrt{s}$ (CM energy)

Range over 15 decades

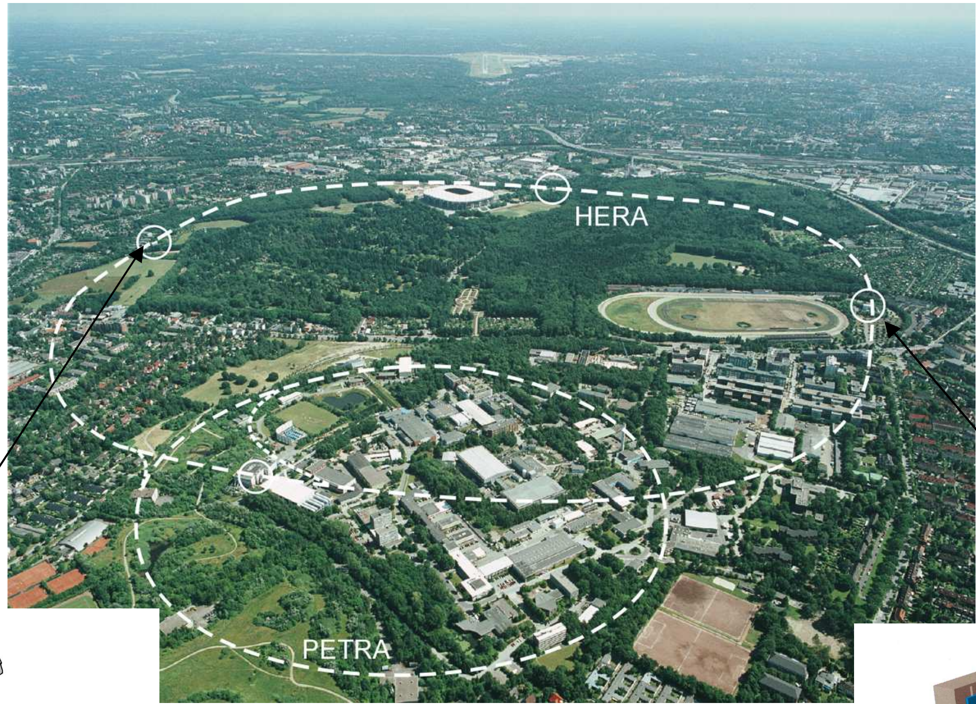
Cross-sections of interest are small

W, Z production

Higgs production for mass 150 GeV

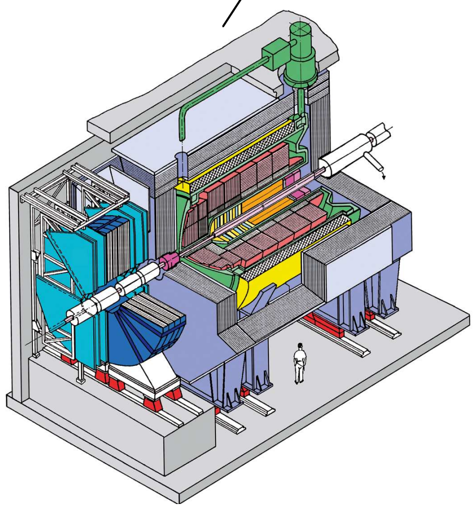
HERA – the microscope

e-p collider
$e^{+/-}$ 27.5 GeV
p 920 GeV
E_{cm}= 318 GeV

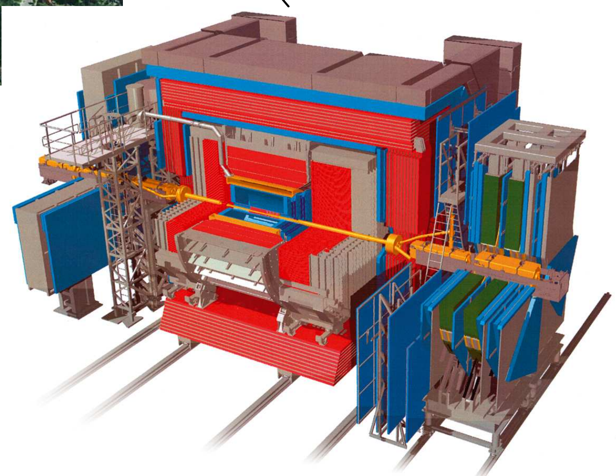


Circumference
~ 11 km

H1 detector



ZEUS detector



γ & Z^0 probes with $e^{+/-}$ (NC)

$$\sigma^{NC}(e^\pm p) = \frac{2\pi\alpha^2}{xQ^4} Y_+ \sigma_r(e^\pm p); \qquad \sigma_r(e^\pm p) = F_2 \mp \frac{Y_-}{Y_+} xF_3 - \frac{y^2}{Y_+} F_L$$

$y = Q^2/sx$ $\qquad$ $Y_\pm = 1 \pm (1-y)^2$ $\qquad$ F_L only important at large y

At HERA only need γ^* exchange and γ^*-Z^0 terms; ignore pure Z^0 exchange

$$F_2 = \sum_q \left\{ e_q^2 - 2 e_q v_e v_q \chi \right\} x(q + \bar{q}) \quad \Leftarrow \quad v_e \text{ small}$$

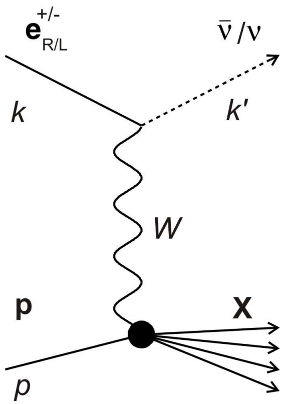
$$xF_3 = -2 a_e \chi \sum_q e_q a_q x(q - \bar{q}) \quad \Leftarrow \quad \text{+ve for u quark} \Rightarrow \sigma_r(e^- p) > \sigma_r(e^+ p)$$

e_q is quark charge; v_i, a_i are the Z^0 vector and axial couplings of the fermions

$$\chi = \frac{Q^2}{Q^2 + M_Z^2} \frac{1}{\sin^2 2\theta_W}$$

$\Rightarrow$ $\quad$ $F_2 \sim xS$ ($q\bar{q}$ sea); $xF_3 \sim xq_{\text{valence}}$ (at large Q^2 and x)

$W^{+/-}$ probe with $e^{+/-}$ (CC)



$$e + p \rightarrow \nu + X \quad \text{at } \sqrt{s} = 318 \text{ GeV}$$

$$Q^2 = -(k-k')^2 \quad x = \frac{Q^2}{2p.q} \quad y = \frac{p.q}{p.k} \quad q = k - k'$$

$$\sigma^{CC}(e^{\pm}p) = \frac{G_F^2}{2\pi x}\frac{M_W^4}{(Q^2+M_W^2)^2}\sigma_r(e^{\pm}p) \qquad (Q^2_{min}\text{(data)} \sim 200 \text{ GeV}^2)$$

at leading order σ_r (reduced xsec) is given in terms of PDFs by

$$\sigma_r(e^+p) = x\left[\bar{u} + \bar{c} + (1-y)^2(d+s)\right] \Leftarrow \text{ sensitive to d-type quarks}$$

$$\sigma_r(e^-p) = x\left[u + c + (1-y)^2(\bar{d}+\bar{s})\right] \Leftarrow \text{ sensitive to u-type quarks}$$

Flavour separation on a proton target - no need for n ↔ p isospin invariance

HERA-I NC & CC data

- HERA-I 1992 – 2000 (HERA-II 2004 – 2007)
  - E_e = 27.5GeV throughout
  - E_p = 820GeV 1992-1997, then 920 GeV for 1998 - 2007
- Both H1 and ZEUS measured inclusive DIS cross-sections
  - NC data $0.045 < Q^2 < 30000$ GeV^2; $6.\ 10^{-7} < x < 0.65$
  - CC $200 < Q^2 < \sim 30000$ GeV^2; $0.008 < x < 0.42$
  - corresponds to ~200 pb^{-1} (e^+p); 30 pb^{-1} (e^-p);
- Uncertainties
  - $Q^2 < \sim 200$ GeV^2 systematic errors dominate
  - at larger Q^2, statistical errors dominate

Combined H1 & ZEUS

- Combination of HERA-I (1994-2000) inclusive DIS cross-sections
- Exploit the different technology of the H1 and ZEUS detectors to 'cross-calibrate', and hence reduce the systematic uncertainties
- The basic assumption is that the two experiments are measuring the same cross-sections at the same (x, Q^2) point.
- The method (developed by A. Glazov) uses an iterative χ^2 minimisation taking full account of error correlations, and allowing for systematic uncertainties that are proportional to central values
- Some details
  - 'swim' data points to common (x, Q^2) bins (change << statistical error)
  - move 820 GeV E_p data to 920 GeV
  - uncertainty from F_L, up to 5% at high y

Uncertainties

- Overall three procedural uncertainties

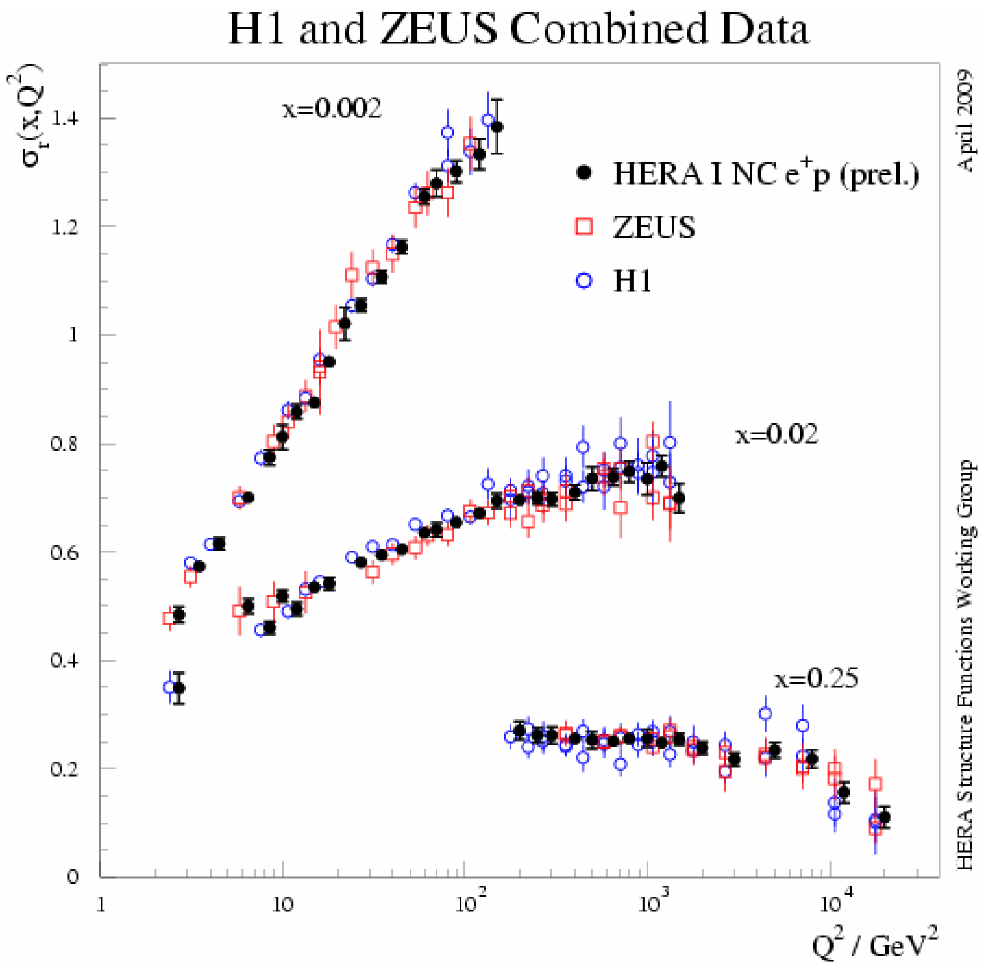
1) Correlated systematic uncertainties (e.g. energy scales),
   - multiplicative (ie proportional to central value) or additive?
   - Try both – gives additional uncertainty < 1% for low Q^2 rising to 1.5% at large Q^2

- Correlations between H1 and ZEUS, (e.g. MonteCarlo simulations, calibration methods..), 12 possible sources identified: most important

2) (~1%) from photoproduction background MC simulation
3) hadronic energy scales

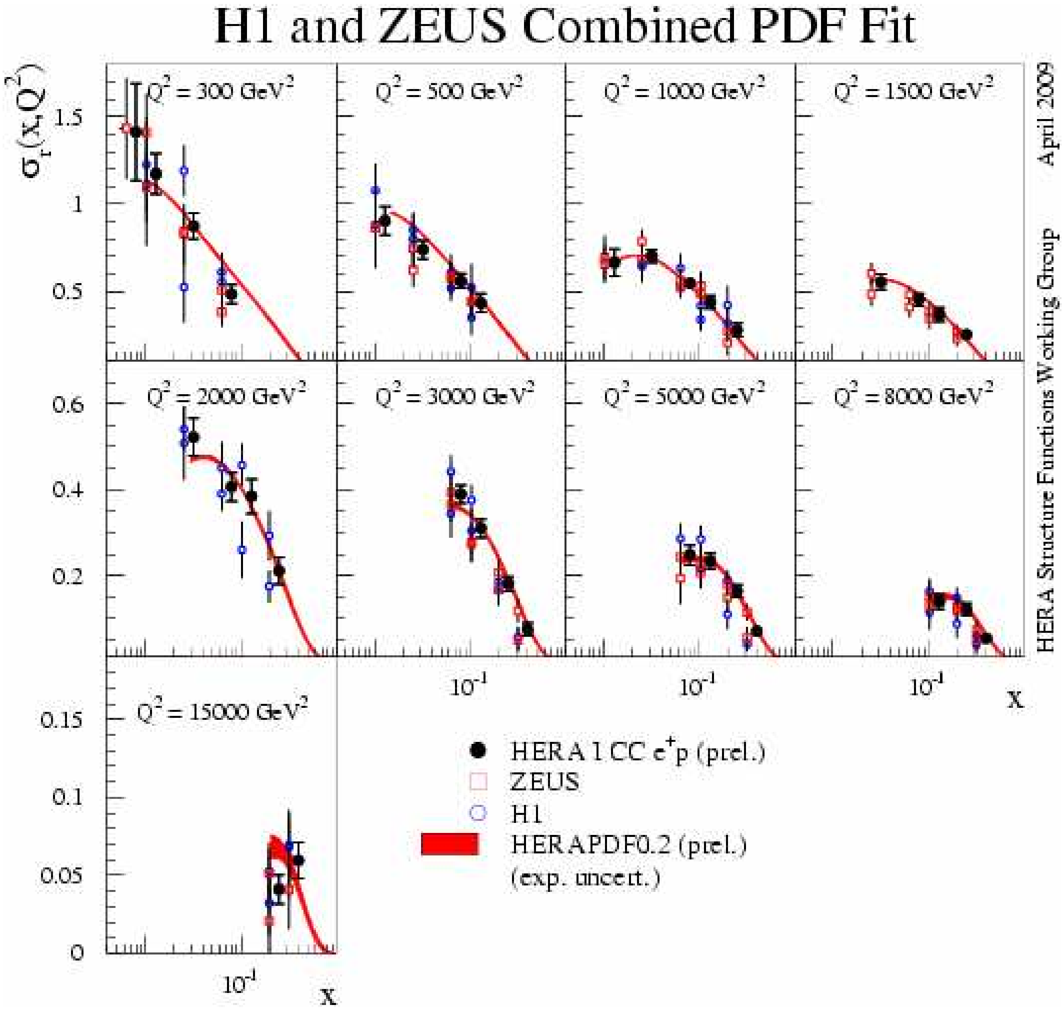
- Statistical & uncorrelated systematic uncertainties added in quadrature
- Overall normalisation uncertainty, common for given experiment and run period

Examples (I): NC e^+p, at fixed *x*



Combined data is smoother than that of either H1 or ZEUS – with significantly smaller uncertainties

CC data



For HERA-I most CC data is statistics limited

Comments on the results

- 1402 input values combined to 741 combined measurements
- Input data are consistent χ^2/dof = 699/716

- Almost all systematic uncertainties reduced, eg
  - H1 LAr Calorimeter energy scale reduced by 55%
  - ZEUS photoproduction background uncert reduced by 65%

- Overall precision improved
  - $3 < Q^2 < 500$ GeV^2, typically better than 2%
  - $20 < Q^2 < 100$ GeV^2, 1% achieved
  - highest Q^2, 10% achieved, increased statistics now important
  - uncertainty also large at high y (small scattered electron energy) because of the photoproduction background

PDF fit to combined HERA-I data

- PDF fits performed by 'professionals' (MSTW, CTEQ...) – also H1 and ZEUS produced fits to own data
  - differ in many details (parameterisation, heavy flavour treatment, uncertainty treatment, use of data from other experiments)
  - results broadly compatible, but the gluon PDFs in particular are different
- Aim now: NLO PDF fit to the combined HERA-I data alone
- Ongoing project by the H1-ZEUS joint team
- HERAPDF0.2 released at DIS 2009 is current best effort
  - uses standard NLO QCD DGLAP formalism for Q^2 evolution
  - need $xf(x,Q_0^2)$ at a starting scale Q_0^2

HERA PDF parameterisation at Q_0^2

$$xf(x, Q_0^2) = Ax^B(1-x)^C(1+Dx+Ex^2+\cdots)$$

	A	B	C	D	E	
xg	sum rule	X	X	-	-	
xu_v	sum rule	X	X	-	Y	
xd_v	sum rule	$=B(xu_v)$	X	-	-	
$x\bar{U}$	$x\bar{u}/x\bar{d} \to 1,\ x \to 0$	X	X	-	-	$x\bar{U} = x\bar{u}\ (+x\bar{c})^\dagger$
$x\bar{D}$	X	$=B(x\bar{U})$	X	-	-	$x\bar{D} = x\bar{d} + x\bar{s}\ (+x\bar{b})^\dagger$

- At Q_0: $x\bar{s} = f_s x\bar{D},\ (f_s = 0.31);\quad A_{\bar{U}} = (1-f_s)A_{\bar{D}};$

  $\dagger\ c\bar{c},\ b\bar{b}$ generated dynamically

Parameter optimisation: start with $A,\ B,\ C$ (X); add $D,\ E$ (Y) until no further reduction in χ^2, only $E_{uv} \neq 0$ required $\Rightarrow$ 10 free parameters

More details

- Further fixed parameters:

  $Q_0^2 = 1.9\ \text{GeV}^2$ (input scale, must be $< m_c^2$)

  $\text{Q}_{\text{min}}^2 = 3.5\ \text{GeV}^2$ (for data included in the fit)

  $m_c = 1.4$ GeV(charm mass), $m_b = 4.75$ GeV(beauty mass)

  $\alpha_{\text{S}}(M_Z) = 0.1176$ (PDG 2006 value)

- NLO QCD (DGLAP) for evolving PDFs to data *(x, Q^2)*
- heavy flavours: Roberts-Thorne general-mass variable flavour number framework (and checked against ACOT (CTEQ) scheme)
- Renormalisation and factorisation scales: Q^2
- PDF parameters determined by χ^2 minimisation

Error/uncertainty treatment

- Combined data have much reduced errors, systematic uncertainties smaller than statistical across most of (x, Q^2) plane
- Different methods of treating the correlated systematic errors (Hessian, offset, add in quadrature) do not make much difference
- Form of the χ^2 function is consistent with that used for the combination
- Combine 110 systematic uncertainties of the data with their statistical uncertainties in quadrature, then offset the 3 procedural uncertainties. Gives $\chi^2/dof = 576/582$ for the central fit

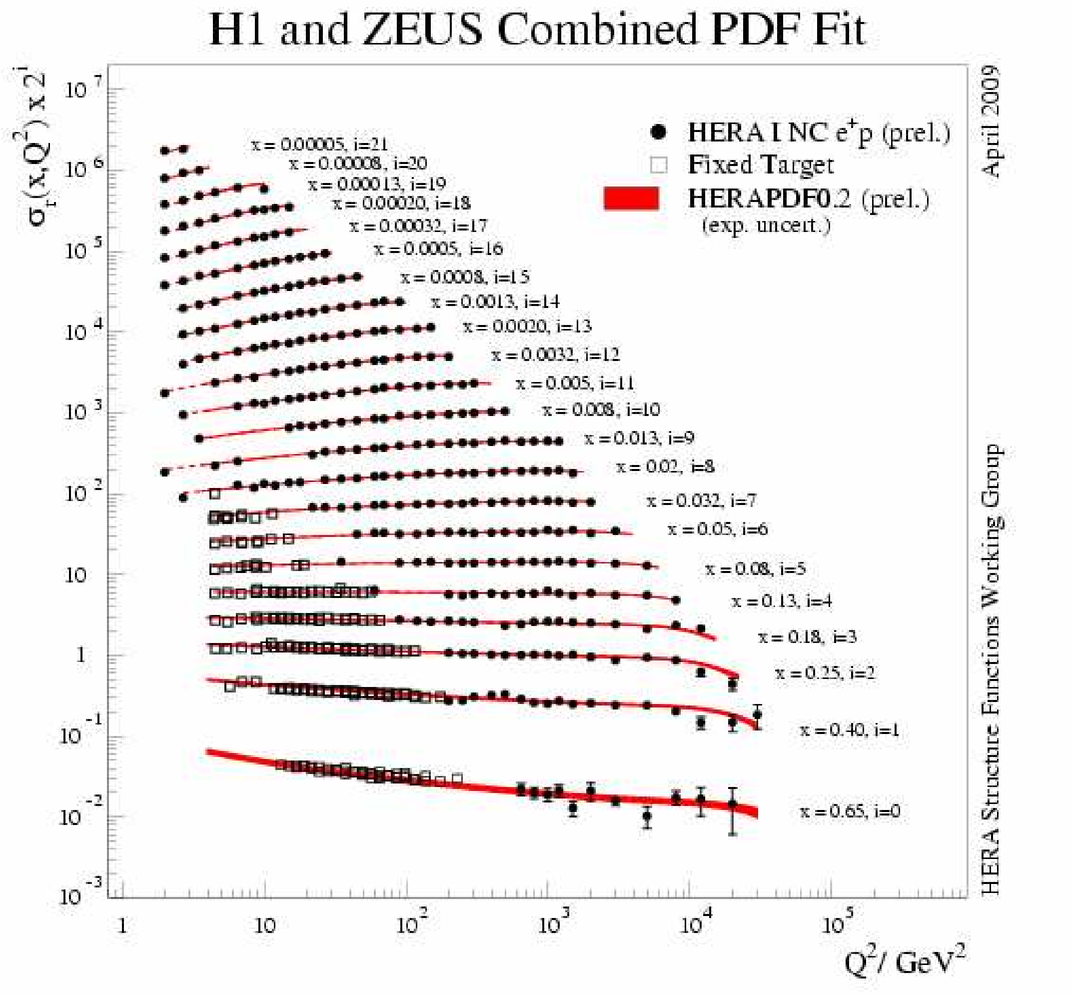
- The self consistency and small systematic uncertainties of the combined data allows the use of $\Delta\chi^2 = 1$ to calculate PDF parameter uncertainties

PDF fit I
NC

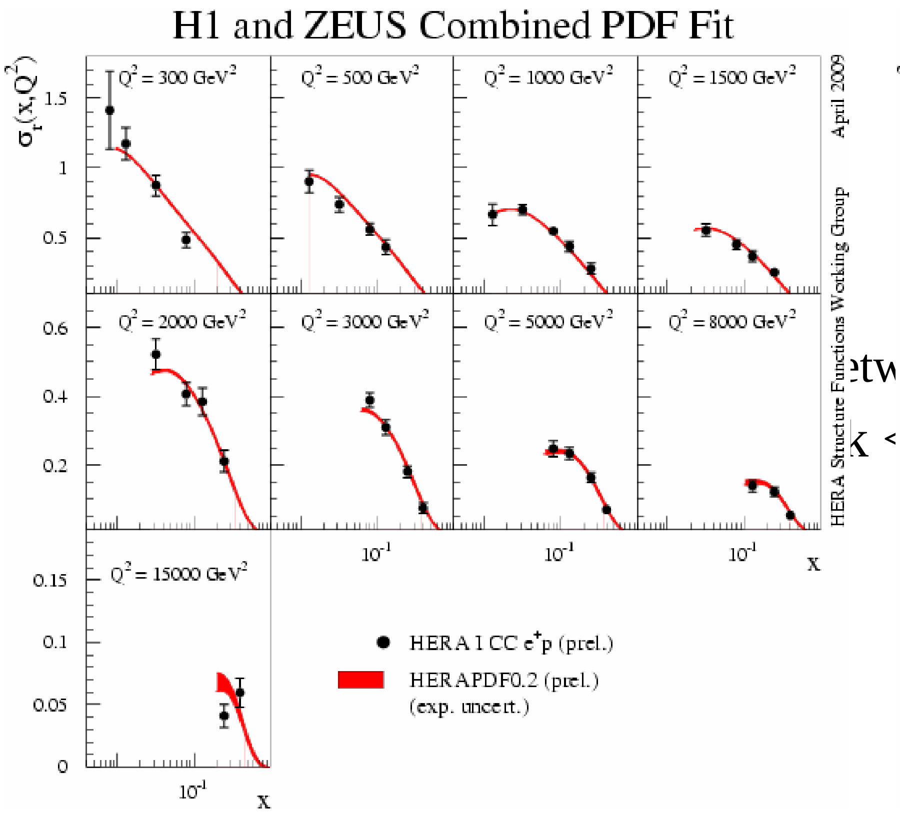
HERAPDF0.2 fit quality to the combined HERA-I data for NC e+p

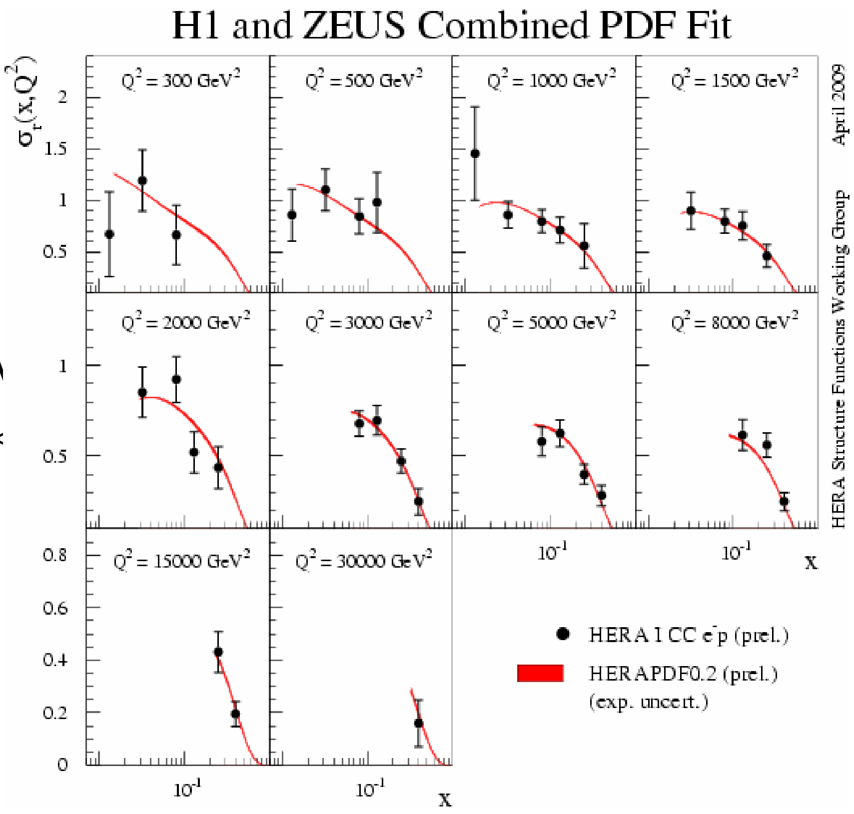
uncertainty from data only

extrapolation to fixed target data



PDF fit II – CC





$\sigma_r(e^+p) = x\left[\bar{u} + \bar{c} + (1-y)^2(d+s)\right]$ $\Leftarrow$ sensitive to d-type quarks (left plots)

$\sigma_r(e^-p) = x\left[u + c + (1-y)^2(\bar{d}+\bar{s})\right]$ $\Leftarrow$ sensitive to u-type quarks (right plots)

Further uncertainties

- Model uncertainties

m_c (1.40): 1.35 $\rightarrow$ 1.50 GeV (Q_0^2 : 1.77, 2.19)

m_b (4.75): 4.3 $\rightarrow$ 5.0 GeV

f_s (0.31): 0.23 $\rightarrow$ 0.38

Q_0^2 (1.9) : 1.5 $\rightarrow$ 2.5 GeV^2 (both f_s and m_c varied)

$Q^2_{\min}$ (3.5) : 2.5 $\rightarrow$ 5.0 GeV^2

- Parameterisation uncertainties

  Consider 11 parameter fits with $E_{uv} \neq 0$ and an extra D or E. Include those with significant deviation from central fit in uncertainty profile - effect is mostly at large x

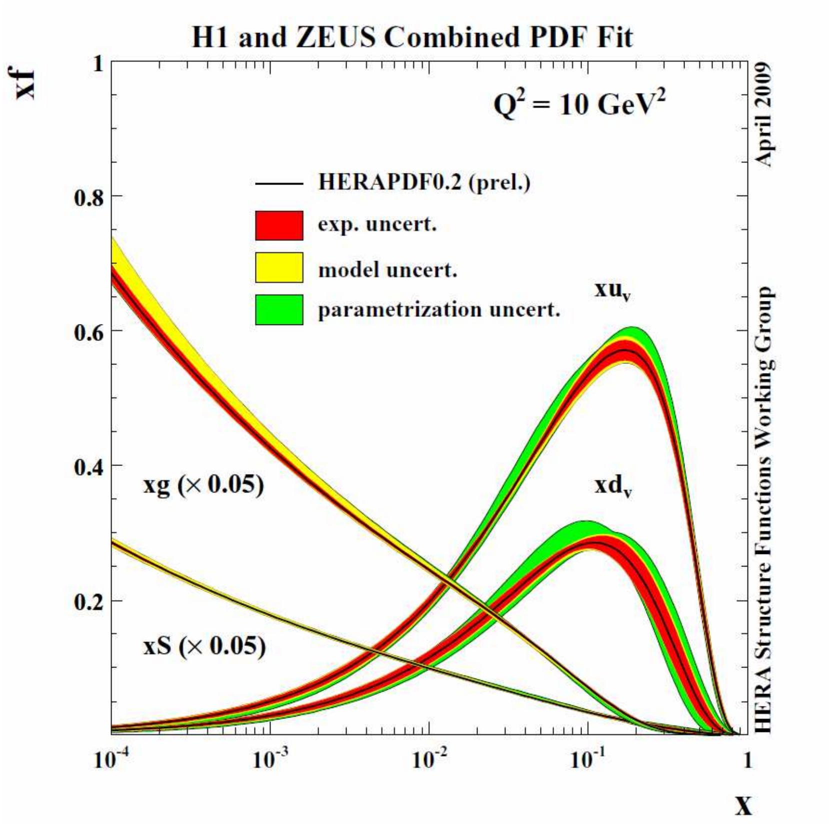
- Vary $\alpha_S(M_Z)$ (0.1176) : 0.1156 $\rightarrow$ 1196 (as a check)

Overview of PDFs at Q^2=10 GeV^2

- PDFs plotted $xu_v,\ xd_v$
  $xS = 2x(\bar{U}+\bar{D}),\ xg$

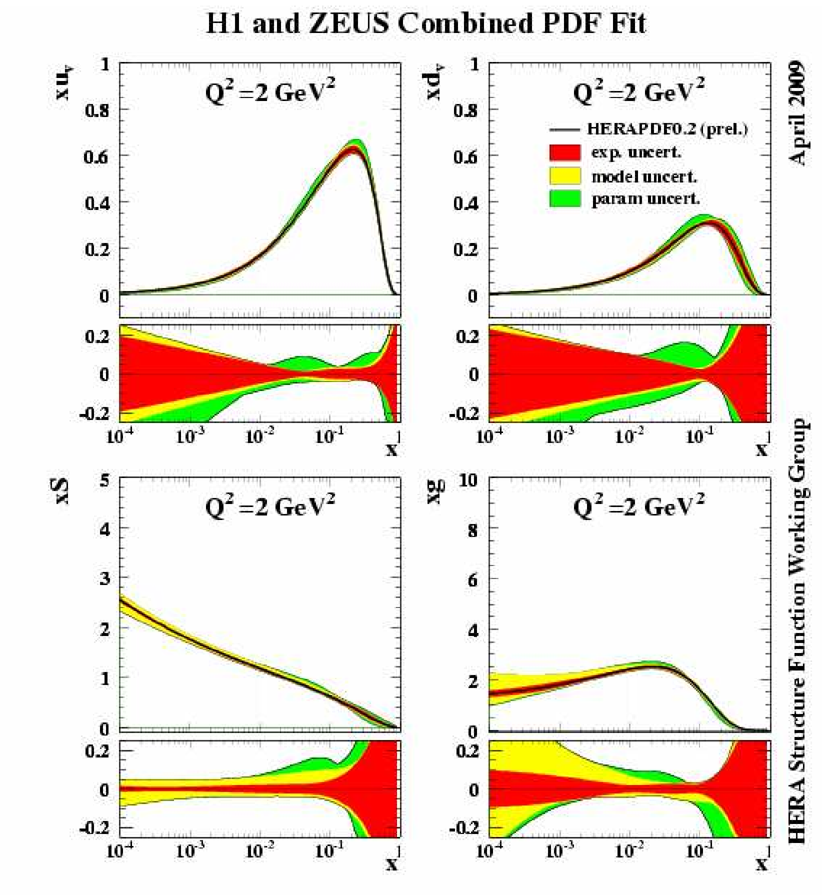
- Model uncertainties (yellow) dominate at low x: xg and xS
  mainly from Q_0^2 changes

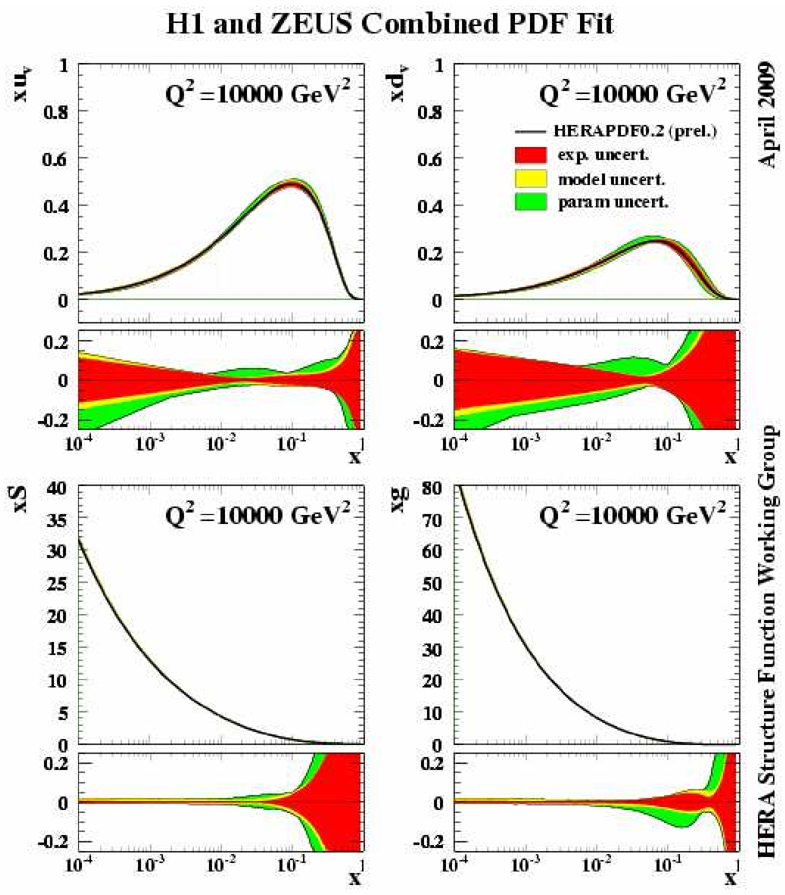
- Parameterisation uncertainties (green) more important and large x:
  $xu_v,\ xd_v$
  (extra polynomial terms $\ldots + Dx + Ex^2$)



- Note the scaling factors on xg and xS.
  Already by this Q^2, proton structure for $x < 0.1$ is dominated by gluons and the $q\bar{q}$ sea

Evolution in Q^2 from starting scale



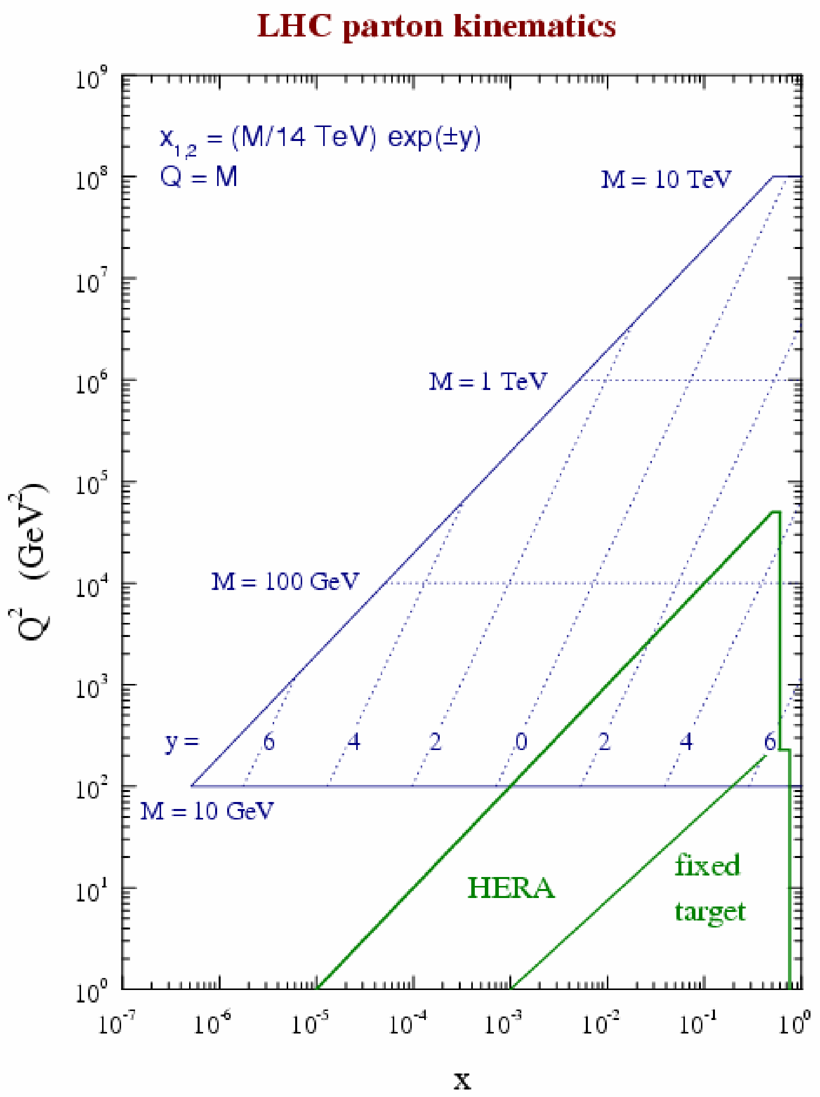


PDFs plotted $xu_v,\ xd_v$ (top plots); $xS = 2x(U + D),\ xg$ (bottom two)

Left: $Q = \sqrt{2}$ GeV, $xg < xS$ as $x \to 0$

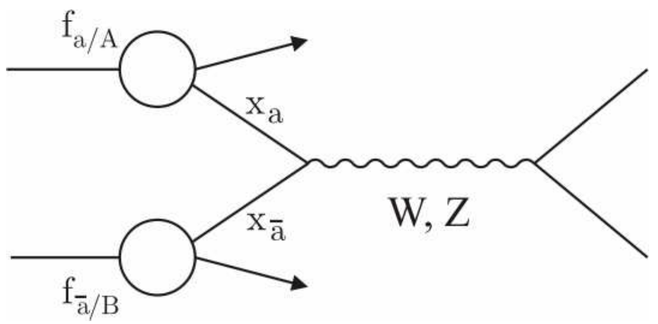
Right: $Q = 100$ GeV xg and xS dominant
uncertainties small except at large x

LHC kinematic region – x vs $(Q=M)^2$

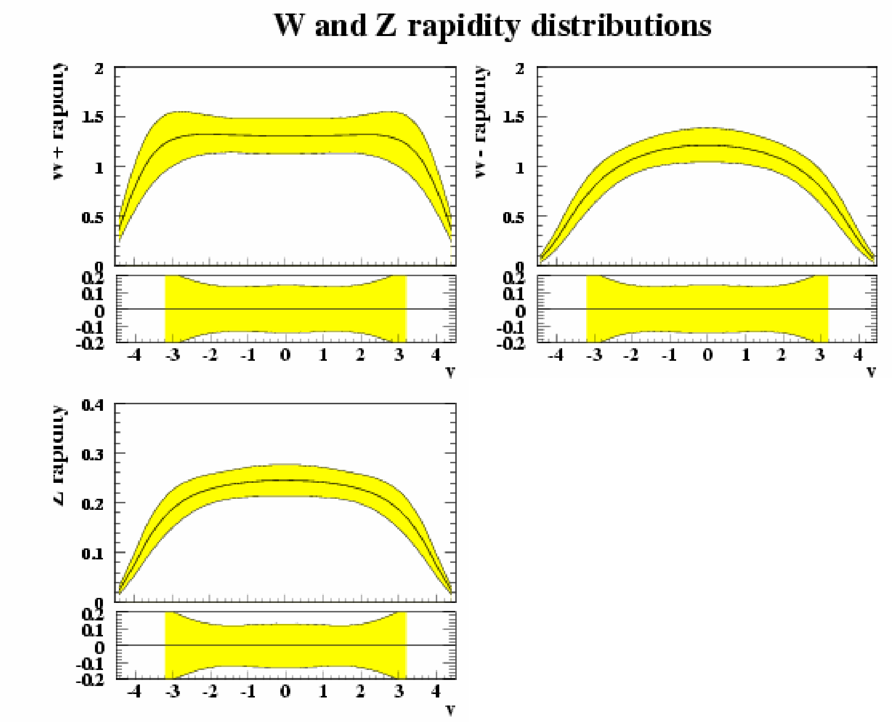


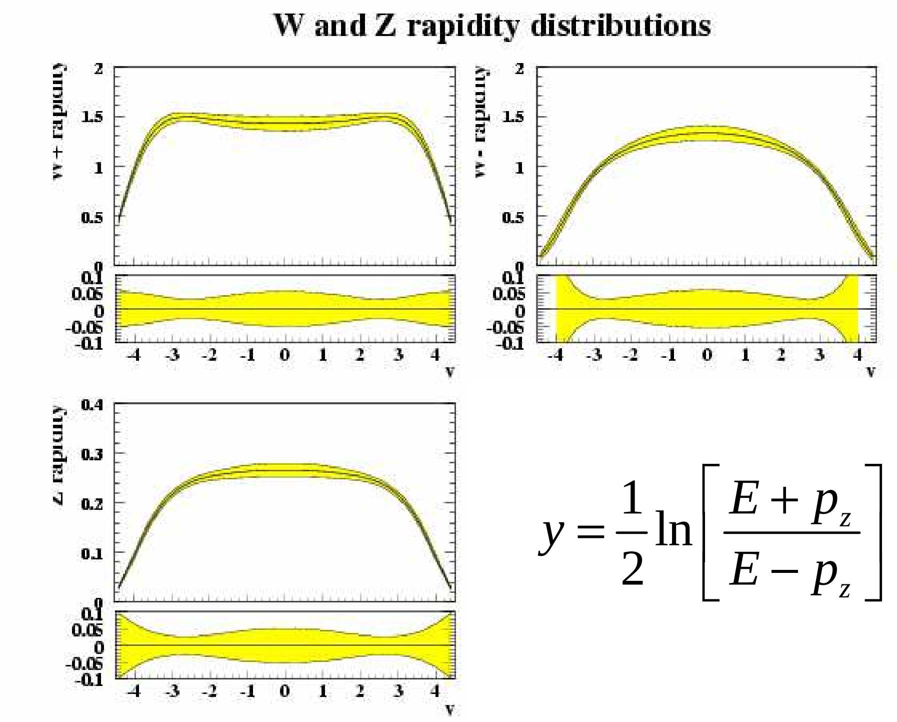
LHC mass scales ~100 GeV
require PDFs x ~ 10^{-4} – 10^{-2}
xg and xS

Focus on Standard Model
W & Z production – likely
to be a benchmark for early
LHC performance



W & Z at 14 TeV – with and w/o HERA input





$$y = \frac{1}{2}\ln\left[\frac{E + p_z}{E - p_z}\right]$$

PDF predictions without HERA data – relative uncertainty bands

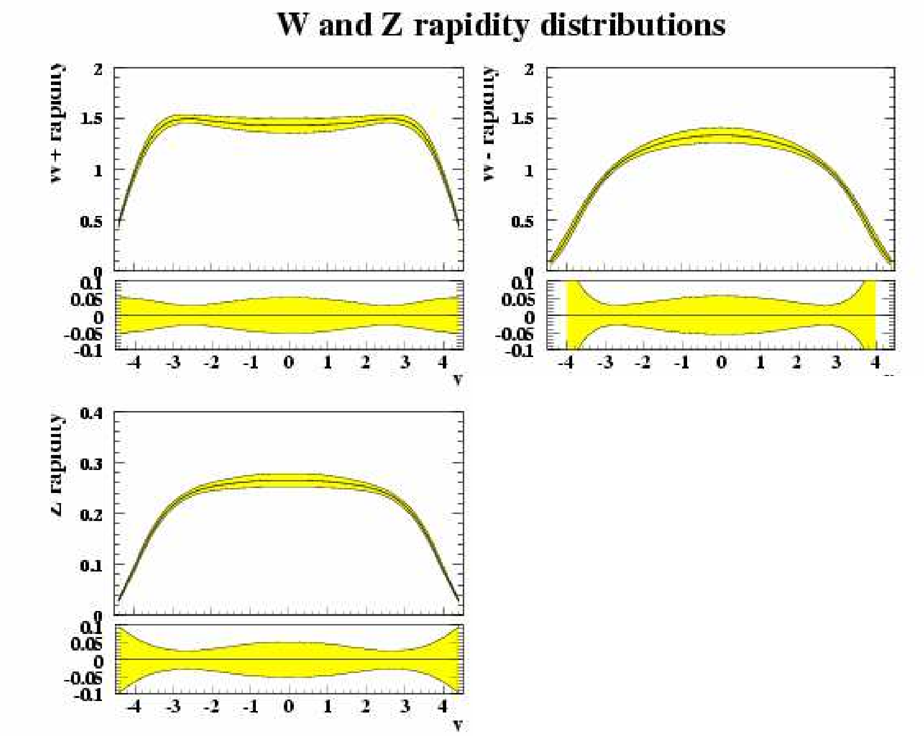
scale +/- 20%

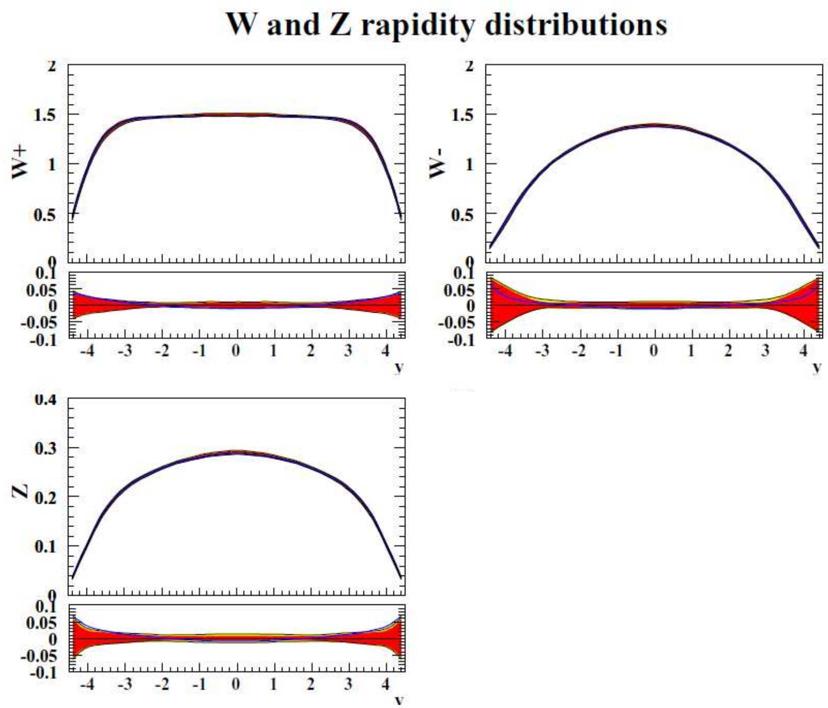
ZEUS-jets PDF (2005)

relative uncertainty bands

scale +/- 10%

W & Z at 14 TeV – HERAPDF





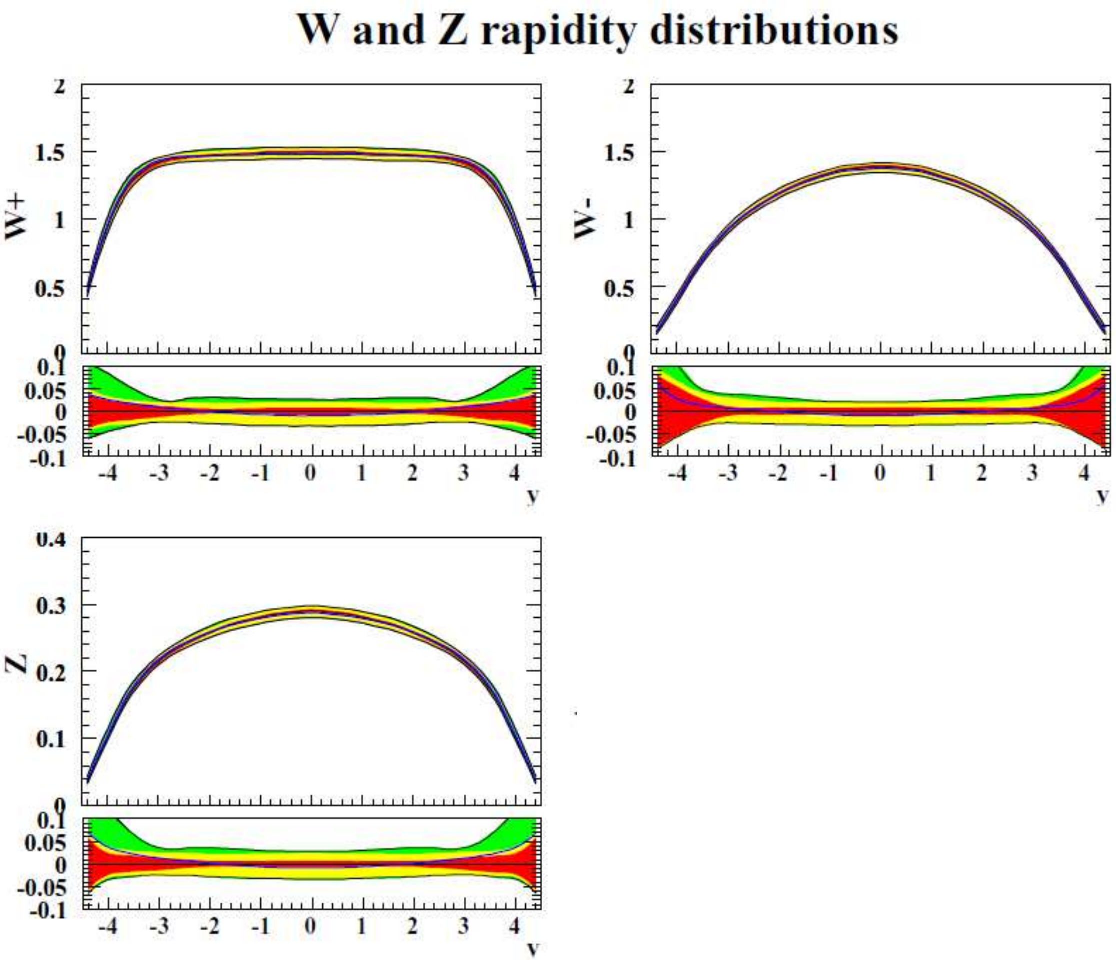
ZEUS-jets PDF

HERAPDF0.2

Only data errors being shown

Uncertainty at central rapidities ~1%

Include all PDF uncertainties



Include all PDF

uncertainty ~2%

Uncertainties:

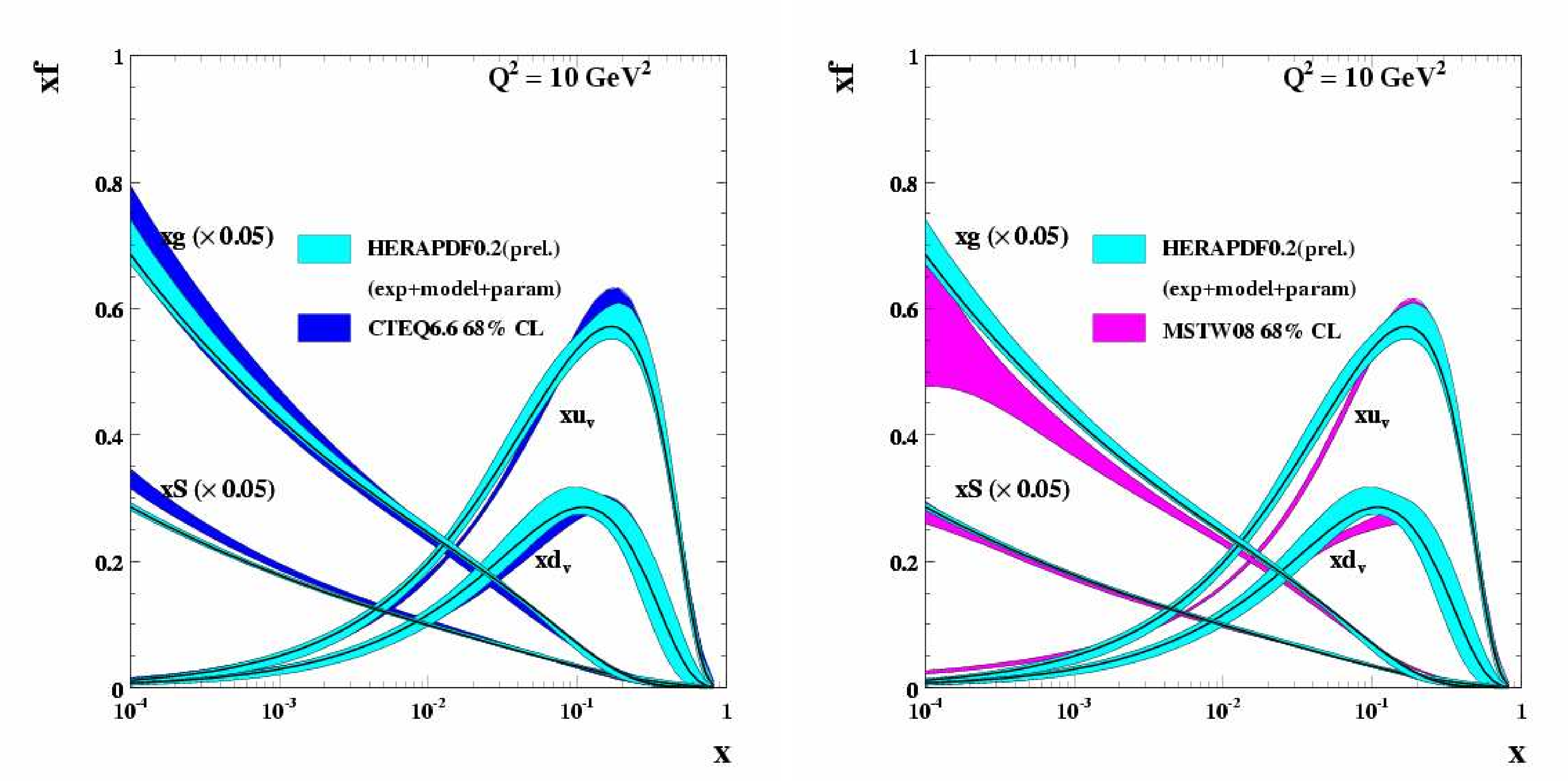
Data: red

Model : yellow

Param.: green

Note the increase in uncertainty at large |rapidity| <> large *x*

Comparisons: CTEQ, MSTW



Error bands at 68% CL: CTEQ & MSTW data uncertainty only

HERAPDF plus model & param. uncertainties

MSTW: *xg* behaviour at low *x* <> form of parameterisation

Summary

- HERA-I DIS NC & CC data combined
  - significantly reduced sys and stat errors
- HERAPDF0.2 fit to this data alone
  - partons agree with those of global teams, but smaller uncertainty
  - model and parameterisation uncertainties now significant
  - significant addition to LHC calculation framework
  - for details: HERA-LHC & PDF4LHC workshops

- Both data and PDFs will be released later this year

- Longer term (< two years?) include HERA-II high Q^2 data
  - fourfold increase in luminosity and polarised $e^{+/-}$ beams

EXTRAS

Input data

Data Set		x range		Q^2 range GeV^2		$\mathcal{L}$ pb^{-1}	Mode	$\sqrt{s}$ GeV	ref.
H1 svx-mb	95-00	5×10^{-6}	0.02	0.2	12	2.1	e^+p	301-319	[5]
H1 low Q^2	96-00	2×10^{-4}	0.1	12	150	22	e^+p	301-319	[10]
H1 NC	94-97	0.0032	0.65	150	30000	35.6	e^+p	301	[11]
H1 CC	94-97	0.013	0.40	300	15000	35.6	e^+p	301	[11]
H1 NC	98-99	0.0032	0.65	150	30000	16.4	e^-p	319	[14]
H1 CC	98-99	0.013	0.40	300	15000	16.4	e^-p	319	[14]
H1 NC HY	98-99	0.0013	0.01	100	800	16.4	e^-p	319	[12]
H1 NC	99-00	0.00131	0.65	100	30000	65.2	e^+p	319	[12]
H1 CC	99-00	0.013	0.40	300	15000	65.2	e^+p	319	[12]
ZEUS BPC	95	2×10^{-6}	6×10^{-5}	0.11	0.65	1.65	e^+p	301	[3]
ZEUS BPT	97	6×10^{-7}	0.001	0.045	0.65	3.9	e^+p	301	[4]
ZEUS SVX	95	1.2×10^{-5}	0.0019	0.6	17	0.2	e^+p	301	[7]
ZEUS NC	96-97	6×10^{-5}	0.65	2.7	30000	30.0	e^+p	301	[9]
ZEUS CC	94-97	0.015	0.42	280	17000	47.7	e^+p	301	[16]
ZEUS NC	98-99	0.005	0.65	200	30000	15.9	e^+p	319	[15]
ZEUS CC	98-99	0.015	0.42	280	30000	16.4	e^+p	319	[17]
ZEUS NC	99-00	0.005	0.65	200	30000	63.2	e^+p	319	[13]
ZEUS CC	99-00	0.008	0.42	280	17000	60.9	e^+p	319	[18]

χ^2 for a single data set

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

μ^i measured central value

$\delta_{i,stat}$ statistical uncertainty

$\delta_{i,uncorr}$ uncorrelated systematic uncertainty

γ^i_j relative sensitivity of datum i to systematic j

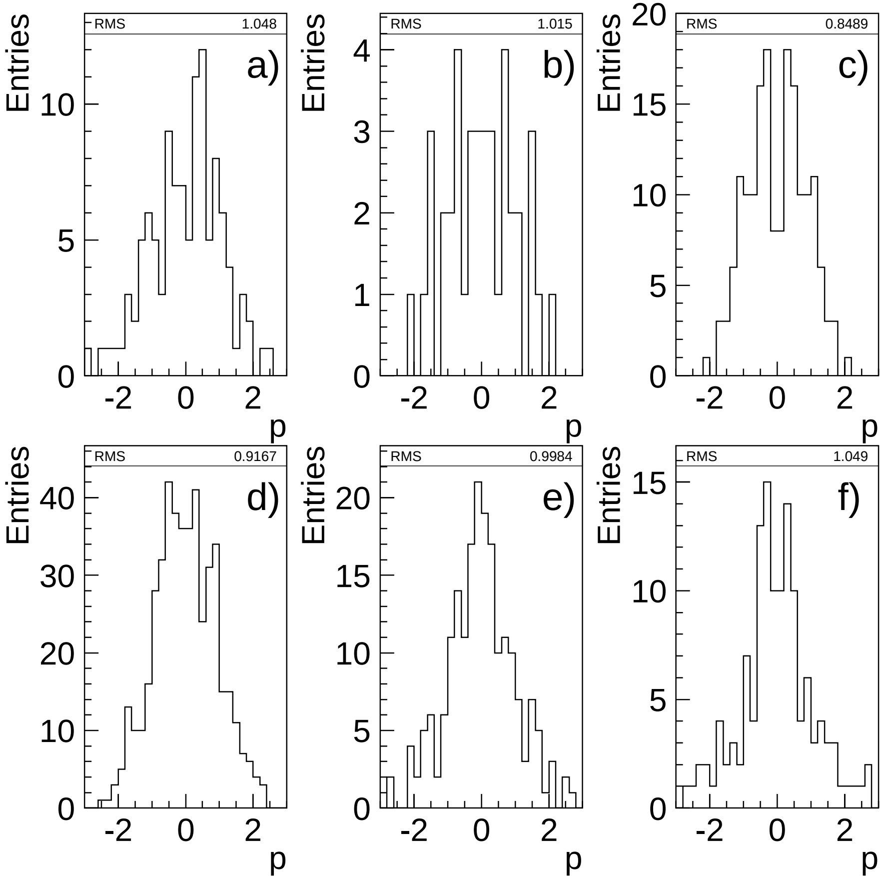
m^i fitted combined H1-ZEUS data

b_j fitted shifts of correlated uncertainties

By definition $\chi^2 = 0$ for $m^i = \mu^i$ and $b_j = 0$;

$Cov(m^i, m^j)$ gives the error matrix for the combined data

Quality of the fit



1153 individual NC, CC data averaged to 573 points

$\chi^2 = 510$

A total of 43 systematic uncertainties from the data and 4 from the averaging procedure

The standard formalism (DGLAP)

$$\frac{\partial \Sigma}{\partial \ln Q^2} = \frac{\alpha_s}{2\pi}\left(\Sigma \otimes P_{qq} + g \otimes P_{qg}\right) \qquad \Sigma = \sum_f (q_f + \bar{q}_f)$$

$$\frac{\partial g}{\partial \ln Q^2} = \frac{\alpha_s}{2\pi}\left(\Sigma \otimes P_{gq} + g \otimes P_{gg}\right)$$

P_{ij} known from QCD (here NLO)

$$\frac{\partial q_f^{NS}}{\partial \ln Q^2} = \frac{\alpha_s}{2\pi} q^{NS} \otimes P_{qq}$$

$q_f, \bar{q}_f, g$ are PDFs to be determined

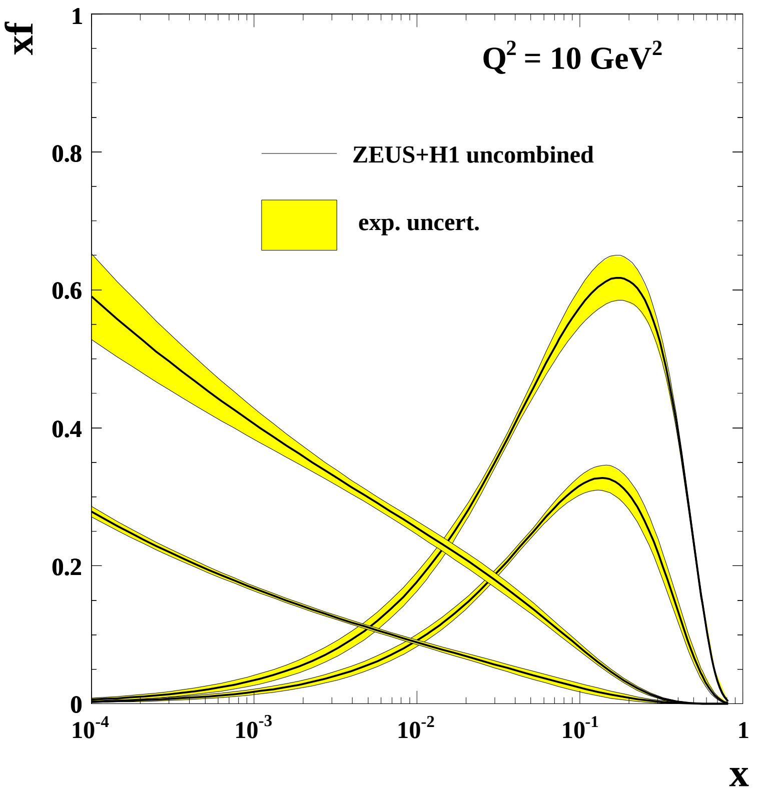
at Q_0^2: $xf(x, Q_0^2) = Ax^B(1-x)^C(1+Dx+Ex^2)$,

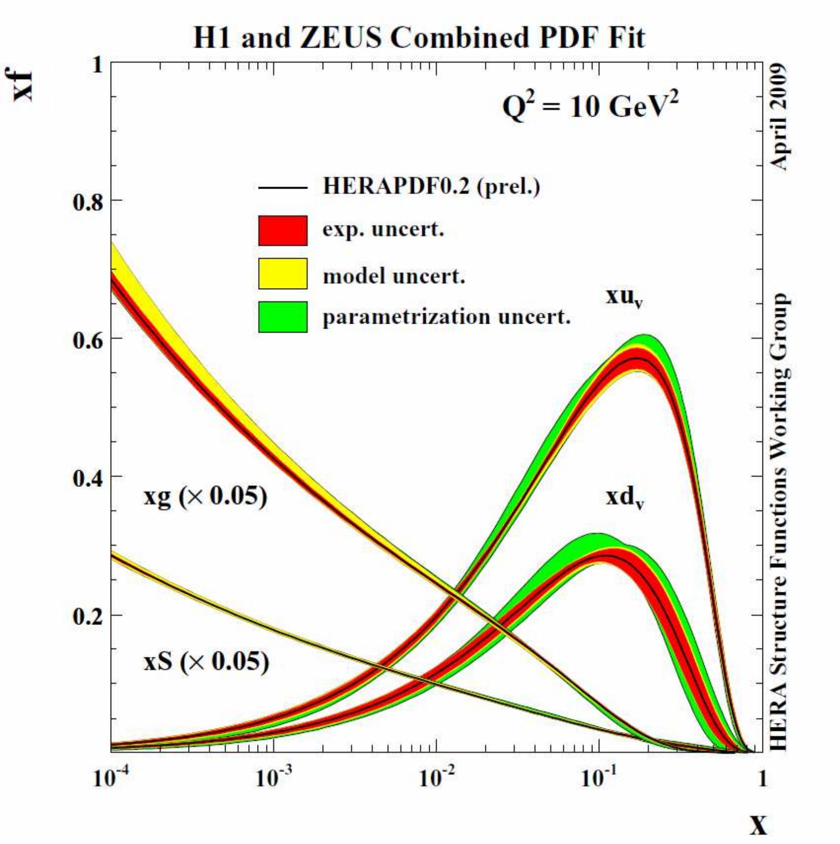
evolve to (x_{data}, Q^2_{data}); calculate observable quantities;

determine the parameters $\{p_i\}$ using χ^2 minimisation

$$F_2 \sim \sum_f e_f^2 x(q_f + \bar{q}_f); \qquad \frac{\partial F_2}{\partial \ln Q^2} \sim \alpha_S\left(Q^2\right) xg(x, Q^2) \Leftarrow \text{getting at the glue}$$

Benefit of combining the data

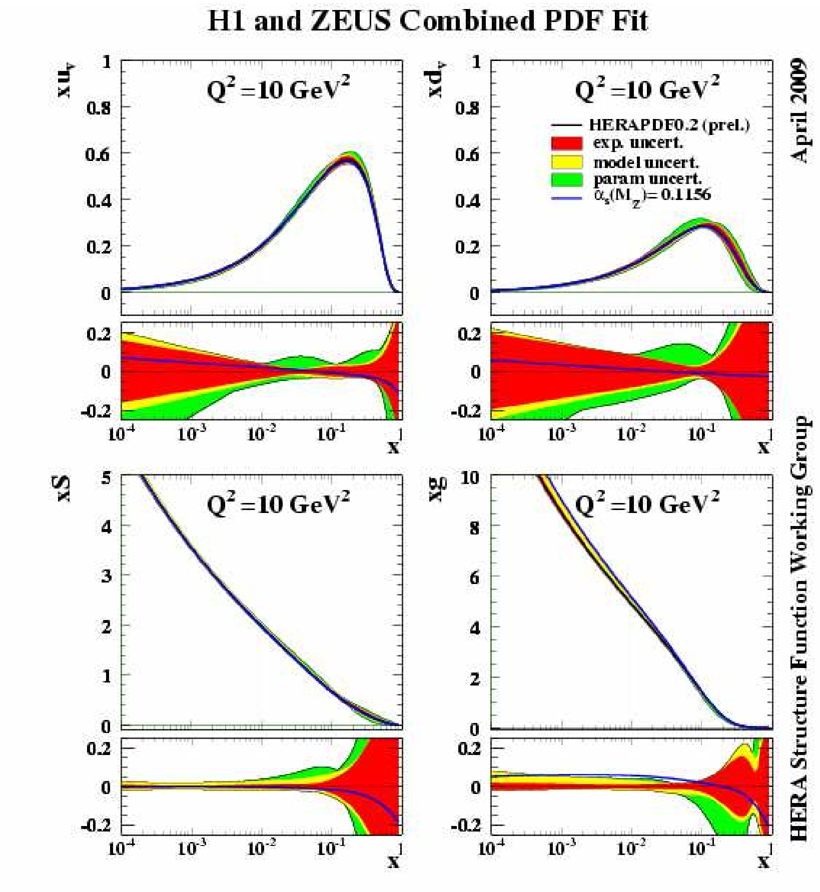


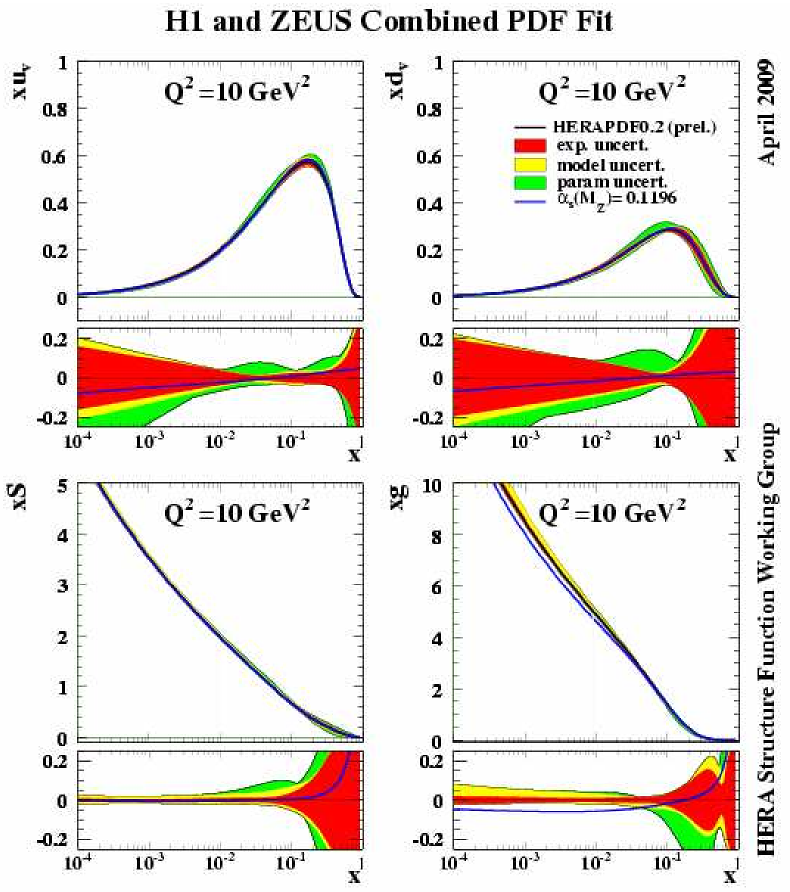


PDF fit to H1 & ZEUS NC & CC data without combination

HERAPDF0.2 – fit to combined data – compare red band here

α_s variation





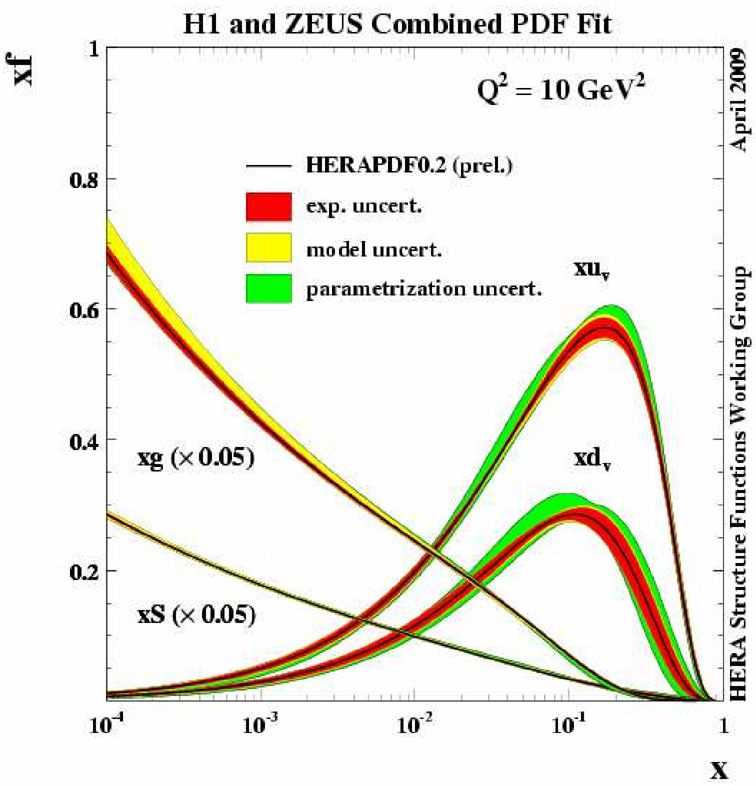
LH plots: $\alpha_S = 0.1176 - 0.002$ RH plots: $\alpha_S = 0.1176 + 0.002$

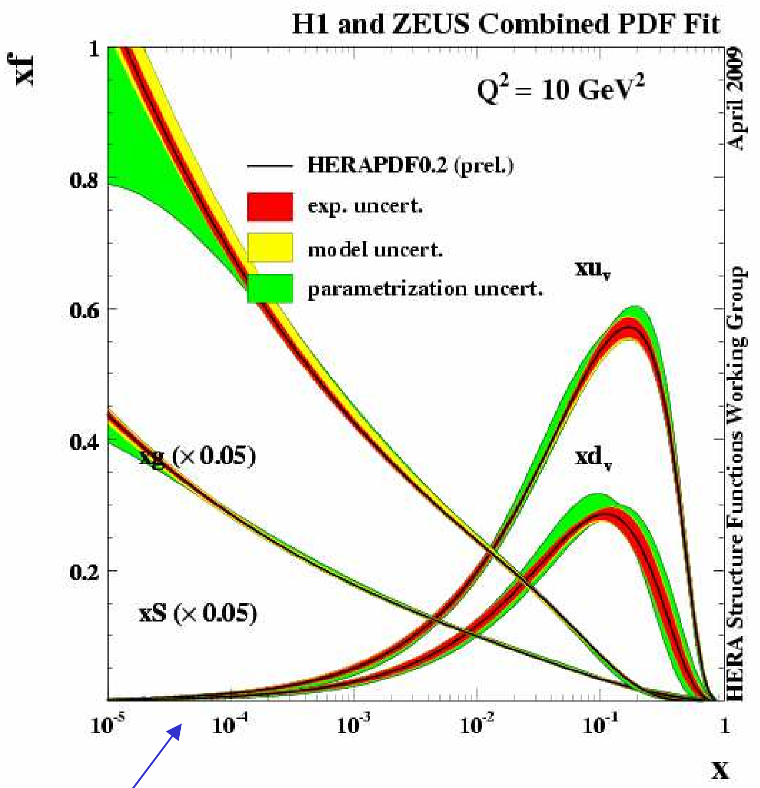
xg is most affected - not surprising with only DIS data fit

Low x – negative gluon?

- Following MSTW, allow xg to go negative at low x

$$xf(x,Q_0^2) = Ax^B(1-x)^C(1+Dx+Ex^2) - A'x^{B'}(1-x)^{25}$$





LH plot shows standard fit

Note that x scale of RH plot is down to 10^{-5} - there is not much difference in quality of fit in region $x > 4\times10^{-4}$ where data are fit