High Q^2 physics at HERA

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On Behalf of the ZEUS and H1 Collaborations

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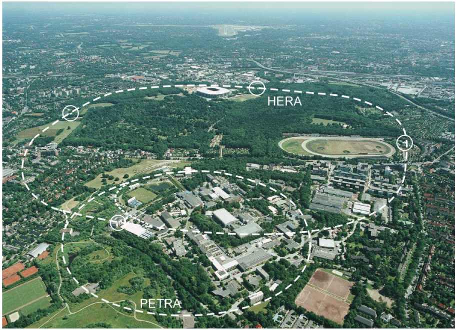
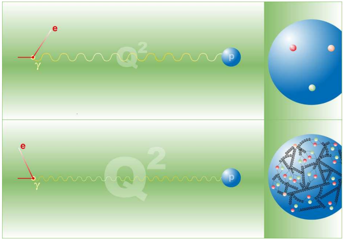
Perimeter Institute for Theoretical Physics, Waterloo, Canada

HERA - the world's only $e^{\pm}p$ collider



- Collides protons with $e^{\pm}$
- $e^{\pm}$ beam: 27.5 GeV
- p beam: 920 GeV
- Centre-of-mass energy $\sqrt{s} = 320$ GeV

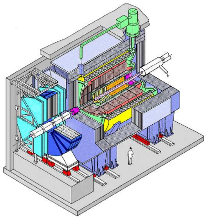
The HERA microscope!

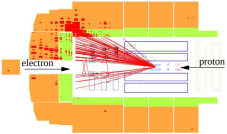


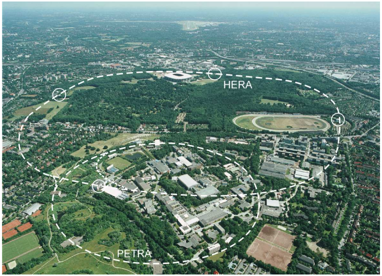
- Q^2 corresponds to the spatial resolution (wavelength λ) of the probe
- $\lambda \sim 1/\sqrt{Q^2}$
- $Q^2_{max} \sim 10^5$ GeV^2 (set by s)
- $\lambda_{min} \sim 10^{-18}$m $\sim R_{\text{proton}}/1000$

The collider detectors at HERA

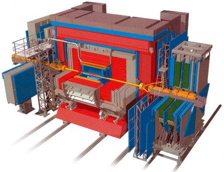
H1

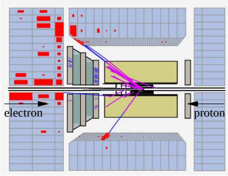






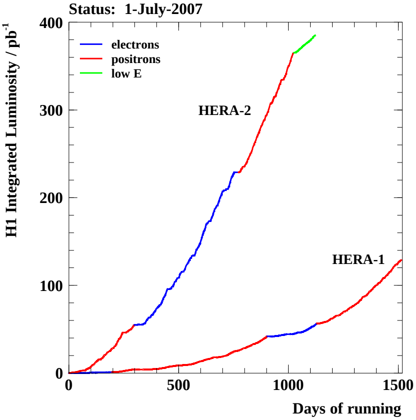
ZEUS

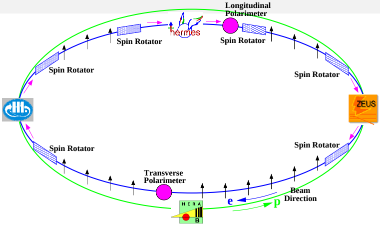




- Compensated Uranium Calorimeter (ZEUS), Liquid Argon Calorimeter (H1)
- Tracking and vertex detectors
- Silicon micro-strip detectors

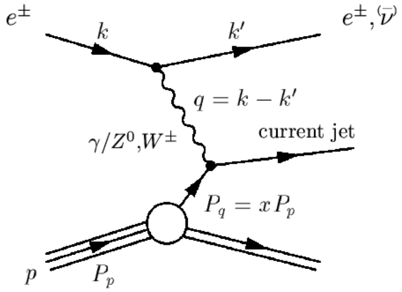
HERA Operation





- Approximately 1 fb^{-1} of data collected by H1 + ZEUS
- Transverse polarisation builds up naturally (Solokov Ternov effect)
- Spin rotators installed in HERA II, providing longitudinally polarised leptons
- $P_e = \frac{N_R - N_L}{N_R + N_L}$

Deep Inelastic Scattering at HERA



Two processes

- Neutral Current (NC): Exchange of γ or Z^0
- Charged Current (CC): Exchange of $W^\pm$

Q^2: Probing power

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

x: Mom. fraction of struck quark

$$x = \frac{Q^2}{2p \cdot q}$$

y: Energy fraction transferred from lepton in p rest frame

$$y = \frac{p \cdot q}{p \cdot k}$$

NC DIS Cross Sections

$$\boxed{\tilde{\sigma}^{e^\pm p}_{NC} = \frac{xQ^4}{2\pi\alpha^2}\frac{1}{Y_+}\frac{d^2\sigma(e^\pm p)}{dxdQ^2} = F_2 \mp \frac{Y_-}{Y_+}xF_3 - \frac{y^2}{Y_+}F_L}$$

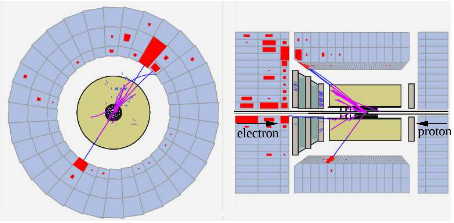
- $Y_\pm \equiv 1 \pm (1-y)^2$
- Structure functions
  - F_2: dominant contribution

    $$\boxed{F_2 \propto \sum(q+\bar{q})}$$
  - xF_3: sensitive at high Q^2

    $$\boxed{xF_3 \propto \sum(q-\bar{q})}$$
  - F_L: sensitive at high y

    $$\boxed{F_L \propto \alpha_s xg(x,Q^2)}$$

ZEUS, NC event



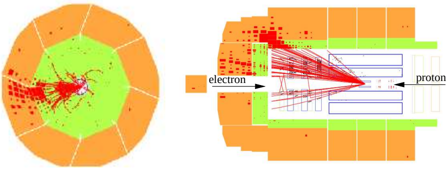
CC DIS Cross Sections

$$\boxed{\frac{d^2\sigma_{CC}(e^-p)}{dxdQ^2} = (1-P_e)\frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2[u+c+(1-y)^2(\bar{d}+\bar{s})]}$$

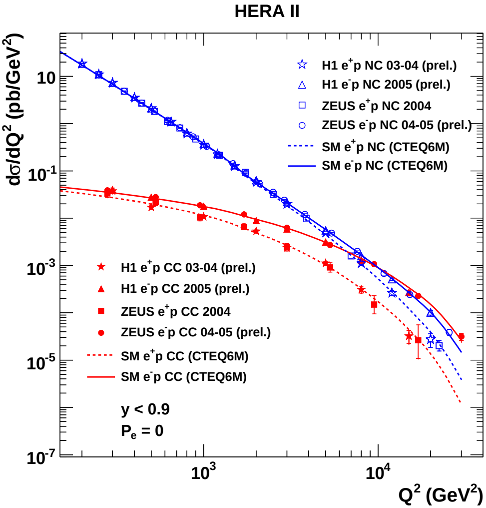
$$\boxed{\frac{d^2\sigma_{CC}(e^+p)}{dxdQ^2} = (1+P_e)\frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2[\bar{u}+\bar{c}+(1-y)^2(d+s)]}$$

- Linear polarisation dependence
- Sensitive to *u and d* valence quarks
  - Flavour dependent probe of proton structure

H1, CC event

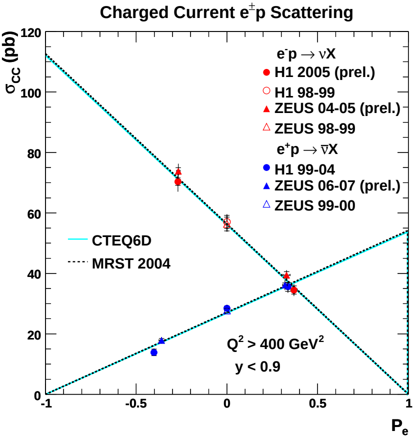


NC & CC Unpolarised Cross Sections



- NC cross section dominated by photon exchange
- Sensitive to the massive Z^0 contribution at high Q^2
- EW unification as NC and CC cross sections become similar

CC Polarised Cross Sections

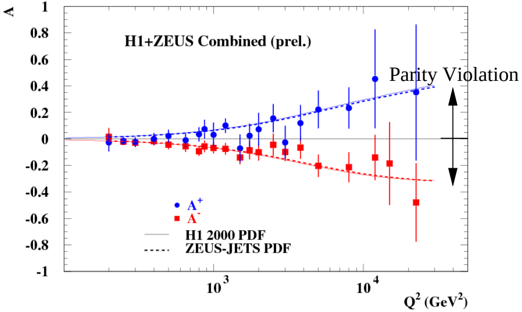


$$\boxed{\sigma_{CC}^{e^{\pm}p}(P_e) = (1 \pm P_e)\sigma_{CC}^{e^{\pm}p}(P_e = 0)}$$

- Linear dependence with lepton polarisation
- No evidence of right-handed currents

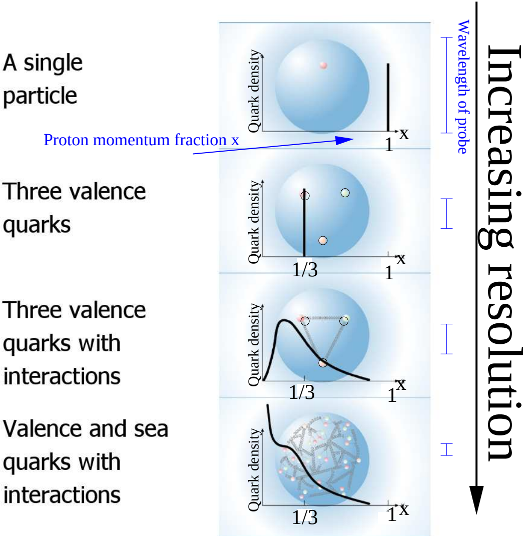
NC Polarisation Asymmetry

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



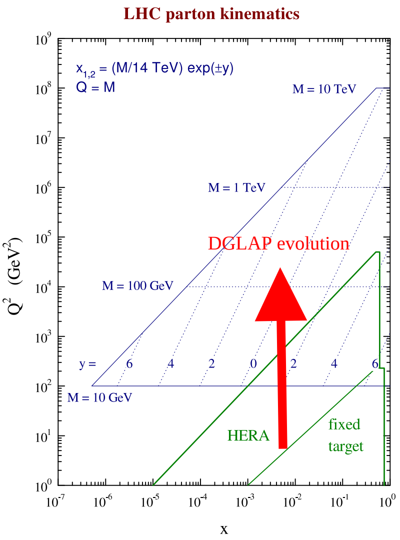
- Observe $A^{\pm} \neq 0$
- First evidence of parity violation in NC $e^{\pm}p$ scattering at high Q^2 ($\sim 10^{-18}$m)

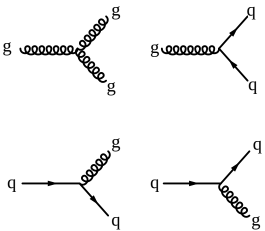
Structure of the proton



- Structure depends on resolution (Q^2)
- Quark density = Probability that a quark carries momentum fraction x
- Known as Parton Density Functions (PDFs)
- Extracted from fits to data (QCD fits)

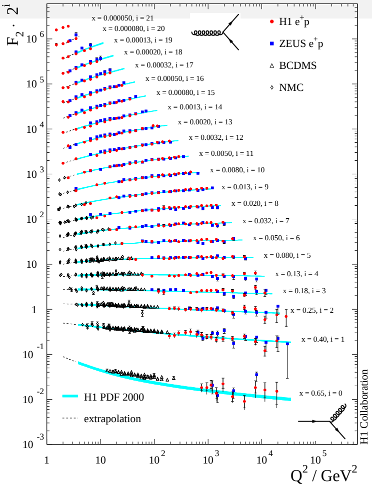
HERA - LHC Kinematic Plane

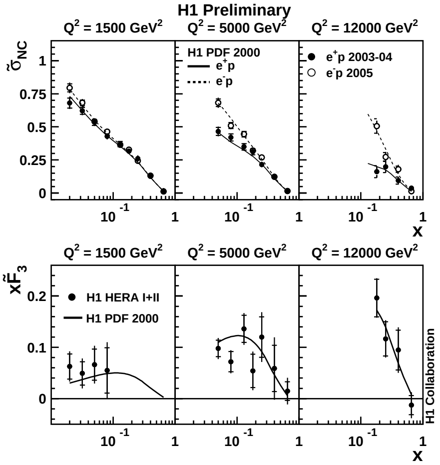




- DGLAP QCD evolution provides Q^2 dependence but x dependence comes from data
- HERA covers a very important region for the LHC
- Reliable PDFs needed to describe the proton structure

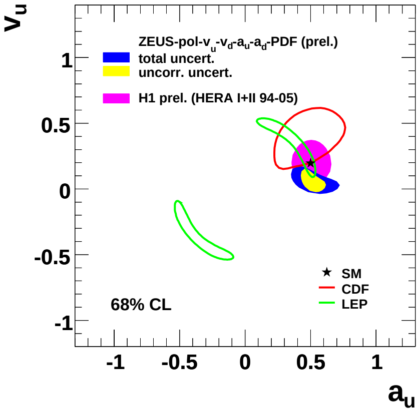
An example of the cross sections used for fits





- Scaling violation
- Low-x sea and gluons precisely determined
- Able to extract $xF_3 \propto \sum(q - \bar{q})$

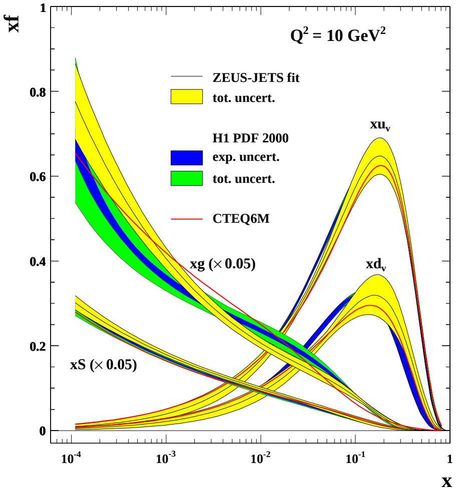
H1 and ZEUS EW fits

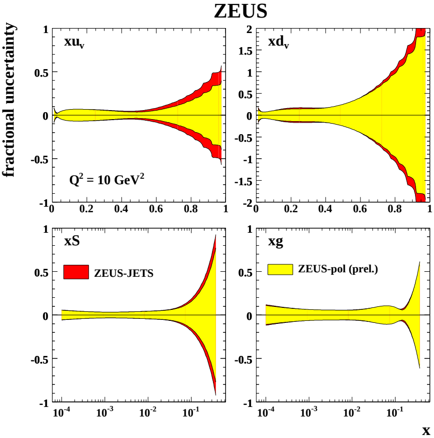


$$\boxed{F_{2,3} = F_{2,3}(v_e, a_e, v_q, a_q)}$$

- Leave the light-quark couplings to the Z^0 free in fit
- Extract vector (v) and axial vector (a) couplings
- Competitive with Tevatron and LEP results

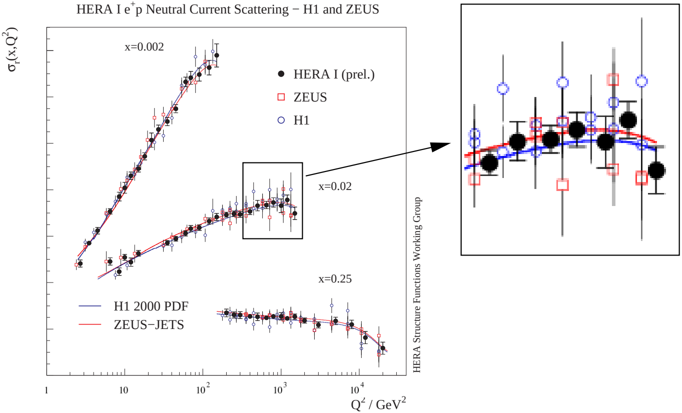
H1 and ZEUS PDF fits





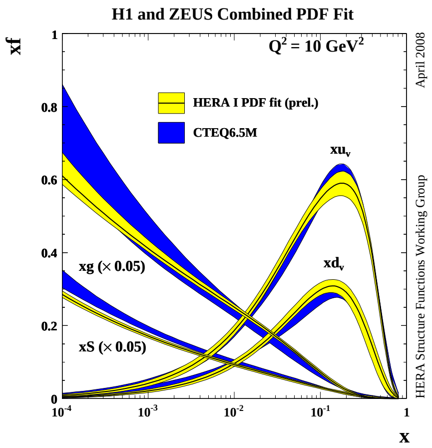
- ZEUS-pol includes new polarised data
- Improved uncertainties

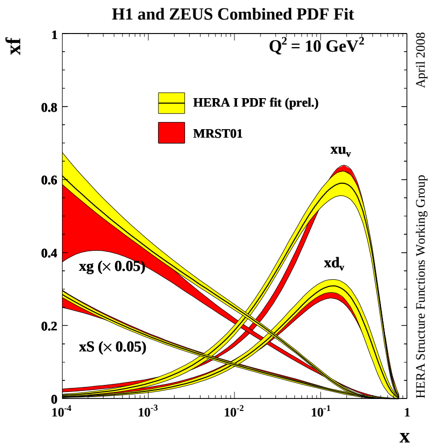
HERA I combined CC and NC results



- H1 and ZEUS are very active in combining DIS results
- Experiments "cross calibrate" each other
  - Uncertainties improved by more than $\sqrt{2}$ in some regions

HERA I PDF





- HERA I PDF fitted using combined H1 and ZEUS data
- Impressive precision compared to global fits

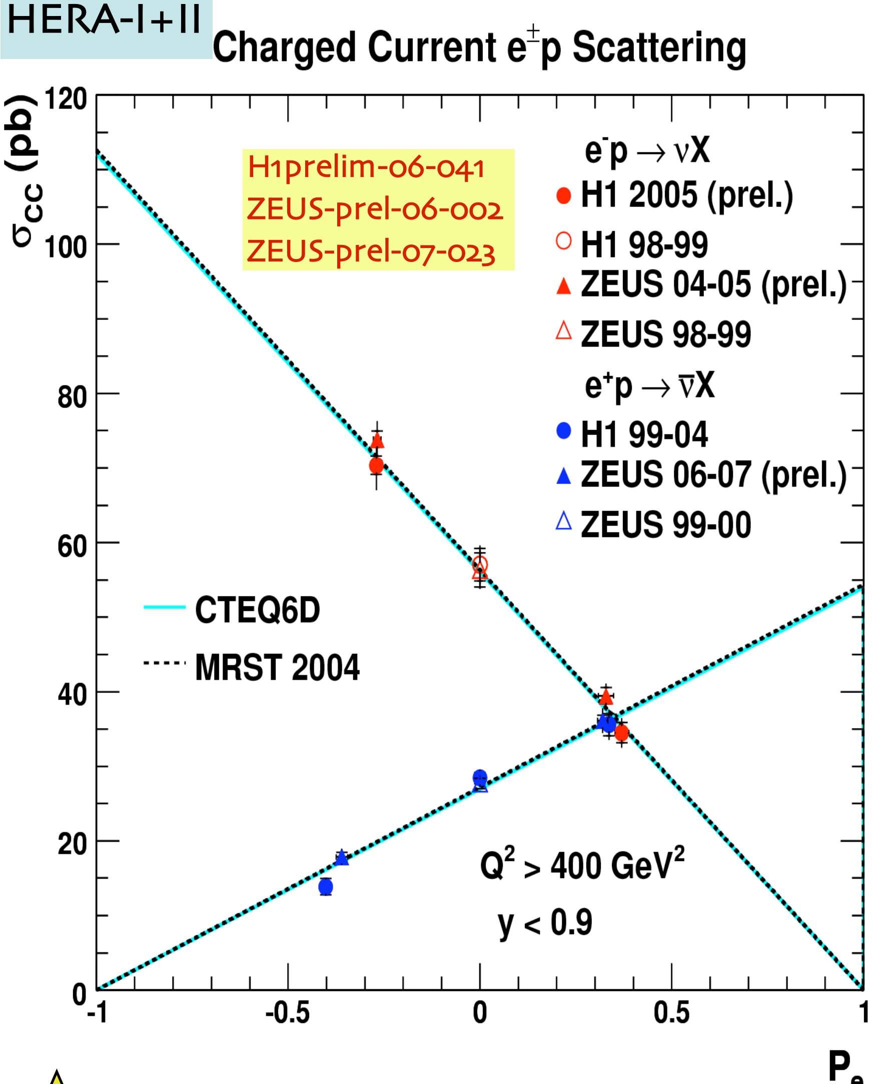
Summary

- HERA is providing significant tests to the electroweak model and improving our knowledge of the proton structure
- No evidence of right-handed CC
- First time that parity violation observed in NC DIS at high Q^2
- Determination of the light quark couplings to the Z^0
- Improvements to PDF uncertainties using HERA II data and through H1 & ZEUS combination

- Outlook
  - Analysis of complete HERA data, $\approx 1fb^{-1}$, to come

CC Polarisation Dependence

HERA-I+II



ZEUS 06-07 (prel.) NEW for EPS07/LP07

$$\sigma^{\pm}_{CC}(P_e) = (1 \pm P_e)\, \sigma^{\pm}_{CC}(P_e = 0)$$

Linear dependence demonstrated

Extrapolation to $P_e = \pm 1$ → limits on RH σ_{CC}

$\sigma_{CC}(e^-p)$ [pb] extrapolated to P_e = +1	
H1 (prel.)	$-0.9 \pm 2.9_{stat} \pm 1.9_{syst} \pm 2.9_{pol}$
ZEUS (prel.)	$0.8 \pm 3.1_{stat} \pm 5.0_{syst+pol}$

$\sigma_{CC}(e^+p)$ [pb] extrapolated to P_e = -1	
H1 (pub.)	$-3.9 \pm 2.3_{stat} \pm 0.7_{syst} \pm 0.8_{pol}$
ZEUS (pub.)	$7.4 \pm 3.9_{stat} \pm 1.2_{syst+pol}$

Consistent with NO RH Charged Currents!

Convert to 95% CL on heavy W_R boson

(assuming $g_L = g_R$ and ν_R is light):

- M_{WR} > 208 GeV (H1, e+p)
- M_{WR} > 186 GeV (H1, e-p)
- M_{WR} > 180 GeV (ZEUS, e-p)

Complementary to Tevatron direct searches

cf. W' > 786 GeV by CDF (W' → eν,μν)

M_W Determination

QCD+EW fit: to determine PDFs and M_W, G_F

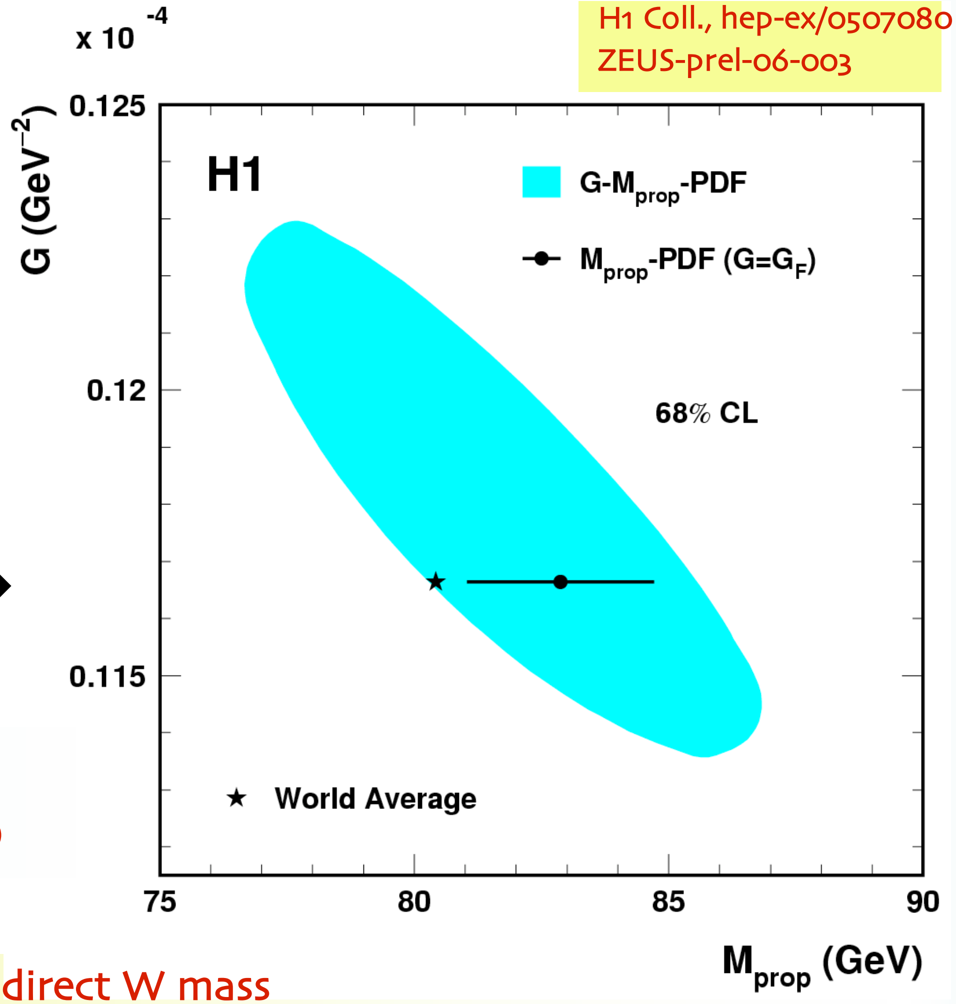
$$\sigma_{CC@HERA} \propto \frac{G_F^2 M_W^4}{(Q^2+M_W^2)^2}$$

Determination of propagator mass in the t-channel (cf. s-channel at LEP/Tevatron):

- Free M_W and G_F:
  G_F consistent with value from μ-decay →
- Fix G_F:

M_W = 82.9 $\pm 1.8_{exp}{}^{+0.3}_{-0.2|model}$ GeV (H1)
M_W = 79.1$\pm 0.8_{uncorr} \pm 1.0_{corr}$ GeV (ZEUS)

H1 Coll., hep-ex/0507080
ZEUS-prel-06-003



Complementary to and consistent with direct W mass measurements from LEP/Tevatron → now measured in spacelike domain

PDG Values:
M_W = 80.4 GeV
G_F=1.16637x10^{-5} GeV^{-2}

Using jet data in PDF fits – pioneering paper H1 Eur.Phys.J.C19(2001)289 but for $\alpha_s(M_Z)$ and gluon PDF only

Where does the information come from in a global fit compared to a fit including only ZEUS data ?

	Global	**HERA Only**
Valence	Predominantly fixed target data (ν-Fe and $\mu D/\mu p$)	High Q^2 NC/CC $e^{\pm}$ cross sections
Sea	Low-x from NC DIS High-x from fixed target Flavour from fixed target	Low-x from NC DIS High-x less precise Flavour ?(need assumptions)
Gluon	Low-x from HERA $dF_2/d\ln Q^2$ High-x from Tevatron jets and momentum sum rule	Low-x from HERA $dF_2/d\ln Q^2$ High-x from jet data and momentum sum rule

ANALYSES FROM HERA ONLY …

— Systematics well understood - measurements from our own experiment

—No complications from heavy target Fe or D corrections

—No assumption on strong isospin

Recap of the method

- $xuv(x) = Au\ x^{av}\ (1-x)^{bu}\ (1 + c_u\ x)$
  $xdv(x) = Ad\ x^{av}\ (1-x)^{bd}\ (1 + c_d\ x)$
  $xS(x) = As\ x^{as}\ (1-x)^{bs}\ (1 + c_s\ x)$
  $xg(x) = Ag\ x^{ag}\ (1-x)^{bg}\ (1 + c_g\ x)$

Parametrize parton distribution functions PDFs at $Q^2_0 = 7\ \mathrm{Gev}^2$ → $x\Delta(x) = x(d-u) = A\Delta\ x^{av}\ (1-x)^{bs+2}$

$$\frac{\partial \mathbf{q_i}(\mathbf{x},\mathbf{Q}^2)}{\partial \log \mathbf{Q}^2} = \frac{\alpha_\mathbf{S}}{\mathbf{2}\pi}\int_\mathbf{x}^\mathbf{1}\frac{\mathbf{dy}}{\mathbf{y}}\Big\{\mathbf{P_{q_iq_j}}(\mathbf{y},\alpha_\mathbf{S})\ \mathbf{q_j}(\frac{\mathbf{x}}{\mathbf{y}},\mathbf{Q}^2) + \mathbf{P_{q_ig}}(\mathbf{y},\alpha_\mathbf{S})\ \mathbf{g}(\frac{\mathbf{x}}{\mathbf{y}},\mathbf{Q}^2)\Big\}$$

Evolve in Q^2 using NLO DGLAP (QCDNUM 16.12) →

$$\frac{\partial \mathbf{g}(\mathbf{x},\mathbf{Q}^2)}{\partial \log \mathbf{Q}^2} = \frac{\alpha_\mathbf{S}}{\mathbf{2}\pi}\int_\mathbf{x}^\mathbf{1}\frac{\mathbf{dy}}{\mathbf{y}}\Big\{\mathbf{P_{gq_j}}(\mathbf{y},\alpha_\mathbf{S})\ \mathbf{q_j}(\frac{\mathbf{x}}{\mathbf{y}},\mathbf{Q}^2) + \mathbf{P_{gg}}(\mathbf{y},\alpha_\mathbf{S})\ \mathbf{g}(\frac{\mathbf{x}}{\mathbf{y}},\mathbf{Q}^2)\Big\}$$

Convolute PDFs with coefficient functions to give structure functions and hence cross-sections →

$$\frac{F_2(x,Q^2)}{x} = \int_0^1 \frac{dy}{y}\left[\Sigma_i C_2^i(z,\alpha_s)\,q_i(x,Q^2) + C_g(z,\alpha_s)\,g(y,Q^2)\right]$$

Coefficient functions incorporate treatment of Heavy Quarks by Thorne-Roberts Variable Flavour Number

Model choices ⇒ Form of parametrization at Q^2_0, value of Q^2_0,, flavour structure of sea, cuts applied, heavy flavour scheme

Fit to data under the cuts,

$W^2 > 20\ \mathrm{GeV}^2$ (to remove higher twist),

$30{,}000 > Q^2 > 2.7\ \mathrm{GeV}^2$ ←Use of NLO DGLAP

$x > 6.3\ 10^{-5}$

The $\chi 2$ includes the contribution of correlated systematic errors

$$\chi^2 = \sum_i \frac{\left[F_i^{QCD}(p) - \sum_\lambda s_\lambda \Delta_{i\lambda}^{SYS} - F_i^{MEAS}\right]^2}{(\sigma_i^{STAT})^2} + \sum s_\lambda^2$$

Where $\mathbf{\Delta_{i\lambda}^{SYS}}$ is the correlated error on point **i** due to systematic error source **λ** and s_λ are systematic uncertainty fit parameters of zero mean and unit variance

This has modified the fit prediction by each source of systematic uncertainty

The statistical errors on the fit parameters, p, are evaluated from $\mathbf{\Delta\chi 2 = 1}$, $s_\lambda=0$

The correlated systematic errors are evaluated by the Offset method –conservative method - $s_\lambda=\pm1$ for each source of systematic error

Now use ZEUS data alone - minimizes data inconsistency (but must consider model dependence carefully)

What is the possible impact of HERA –II data on PDF fits ?

- under currently planned running scenarios hep-ph/0509220

Valence	**High Q^2 inclusive NC/CC $e^{\pm}$ cross sections**
Sea	**Low-x from inclusive NC DIS** **High-x ?**
Gluon	**Low-x from HERA $dF_2/d\ln Q^2$** **Mid-to-high-x from HERA jet data**

More statistics

More statistics and optimized cross-sections?

Currently ~96 pb^{-1} of e+ p NC and CC data –assume 350 pb^{-1}

Currently ~16 pb^{-1} of e- p NC and CC data – assume 350 pb^{-1}

Currently ~37 pb^{-1} of jet data –inclusive DIS and γ-p dijets – assume 500 pb^{-1}

Scale statistical errors from current data- assume systematic errors remain the same

Assume the use of optimised γ-p dijet cross-sections

Based on published data sets (as in summer 2007)

Input data sets : Published HERA I cross sections

data set		x range		Q^2 range (GeV^2)		$\mathcal{L}$ pb^{-1}	comment
H1 NC min. bias	97	0.00008	0.02	1.5	12	1.8	e^+p $\sqrt{s} = 301$ GeV
H1 NC low Q^2	96 – 97	0.000161	0.20	12	150	17.9	e^+p $\sqrt{s} = 301$ GeV
H1 NC	94 – 97	0.0032	0.65	150	30 000	35.6	e^+p $\sqrt{s} = 301$ GeV
H1 CC	94 – 97	0.013	0.40	300	15 000	35.6	e^+p $\sqrt{s} = 301$ GeV
H1 NC	98 – 99	0.0032	0.65	150	30 000	16.4	e^-p $\sqrt{s} = 319$ GeV
H1 CC	98 – 99	0.013	0.40	300	15 000	16.4	e^-p $\sqrt{s} = 319$ GeV
H1 NC	99 – 00	0.00131	0.65	100	30 000	65.2	e^+p $\sqrt{s} = 319$ GeV
H1 CC	99 – 00	0.013	0.40	300	15 000	65.2	e^+p $\sqrt{s} = 319$ GeV
ZEUS NC	96 – 97	0.00006	0.65	2.7	30 000	30.0	e^+p $\sqrt{s} = 301$ GeV
ZEUS CC	94 – 97	0.015	0.42	280	17 000	47.7	e^+p $\sqrt{s} = 301$ GeV
ZEUS NC	98 – 99	0.005	0.65	200	30 000	15.9	e^-p $\sqrt{s} = 319$ GeV
ZEUS CC	98 – 99	0.015	0.42	280	30 000	16.4	e^-p $\sqrt{s} = 319$ GeV
ZEUS NC	99 – 00	0.005	0.65	200	30 000	63.2	e^+p $\sqrt{s} = 319$ GeV
ZEUS CC	99 – 00	0.008	0.42	280	17 000	60.9	e^+p $\sqrt{s} = 319$ GeV

With H1 NC min. bias ($Q^2 < 12$ GeV^2) moved up by 3.4 % after reanalysis of luminosity

Method of combination

- **Move all data points to a common x-Q^2 grid**
- **Move 820 GeV data to 920 GeV beam energy**
- **Calculate the average values and the errors**
- **Evaluate the uncertainties related to the combination method**

Move all data points to x-Q^2 common grid

- Grid : H1 x binning and ZEUS Q^2 binning basically
- Straightforward interpolation :

$$\sigma_{ep}^{meas}(x_{grid}, Q_{grid}^2) = \frac{\sigma_{ep}^{th}(x_{grid}, Q_{grid}^2)}{\sigma_{ep}^{th}(x, Q^2)} \sigma_{ep}^{meas}(x, Q^2)$$

- H1PDF2k and ZEUS-Jets fits have been used. Correction factors agree within a few permille and to better than to 2% for CC.

Move data to 920 GeV beam energy

Beam energy correction for CC data

$$\sigma_{CC\ 920}^{e^\pm p}(x,Q^2) = \sigma_{CC\ 820}^{e^\pm p}(x,Q^2)\frac{\sigma_{CC\ 920}^{th,e^\pm p}(x,Q^2)}{\sigma_{CC\ 820}^{th,e^\pm p}(x,Q^2)}$$

Beam energy correction performed additively for NC data

$$\sigma_{NC\ 920}^{e^\pm p}(x,Q^2) = \sigma_{NC\ 820}^{e^\pm p}(x,Q^2) + \Delta\sigma_{NC}^{e^\pm p}(x,Q^2,y_{920},y_{820}).$$

$$\Delta\sigma e^\pm p_{NC}(x,Q^2,y_{920},y_{820}) = F_L(x,Q^2)\left[\frac{y_{820}^2}{Y_{820}^+} - \frac{y_{920}^2}{Y_{920}^+}\right] + xF_3(x,Q^2)\left[\pm\frac{Y_{820}^-}{Y_{820}^+} \mp \frac{Y_{920}^-}{Y_{920}^+}\right]$$

Systematic error estimated by comparing $F_L = 0$ and $F_L = F_L$(H1PDF2k) :
at present up to 5 % at high y.

Averaging method

- A model independent combination, prior to performing QCD analysis, and which includes full error correlations.

  (A. Glazov – DIS 05 & HERA-LHC WS, code available for other WG)

- The key assumption is that H1 and ZEUS experiments are measuring the same cross sections at the same kinematical points.

- It minimises the following probability distribution $\rightarrow$

χ^2 definition

$$\chi^2_{\exp}\left(M^{i,\mathrm{true}}, \Delta\alpha_j\right) = \sum_i \frac{\left[M^{i,\mathrm{true}} - \left(M^i + \sum_j \frac{\partial M^i}{\partial \alpha_j}\Delta\alpha_j\right)\right]^2}{\sigma_i^2} + \sum_j \frac{\Delta\alpha_j}{\sigma^2_{\alpha_j}}$$

M^i measured central values

σ_i statistical and uncorrelated systematic uncertainties

σ_{α_j} correlated uncertainty

$\frac{\partial M^i}{\partial \alpha_j}$ sensitivity of the data to to the systematic source j

$M^{i,\mathrm{true}}$ fitted H1-ZEUS combined H1-value

$\frac{\partial M^i}{\partial \alpha_j}\Delta\alpha_j$ fitted shift of the **i** data due to the **j** sys error source

It's a cross calibration of the correlated systematics between different data sets. If $\Delta\alpha_j = 0$. it coincides with a standard average

χ^2 definition (cont'd)

$$\chi^2_{\text{exp}}\left(M^{i,\text{true}}, \Delta\alpha_j\right) = \sum_i \frac{\left[M^{i,\text{true}} - \left(M^i + \sum_j \frac{\partial M^i}{\partial \alpha_j}\Delta\alpha_j\right)\right]^2}{\sigma_i^2} + \sum_j \frac{\Delta\alpha_j}{\sigma_{\alpha_j}^2}$$

Caution : Most errors are provided as a relative error but a smaller value of the cross section has a a smaller absolute error $\boldsymbol{\sigma_i}$.

Bias toward smaller averages ! (checked with a toy model)

Can be avoided by modifying chi^2 definition $\longrightarrow$

New χ^2 definition

$$\chi^2_{\exp}\left(M^{i,\mathrm{true}},\Delta\alpha_j\right)=\sum_i \frac{\left[M^{i,\mathrm{true}}-\left(M^i+\sum_j \frac{\partial M^i}{\partial \alpha_j}\frac{M^{i,\mathrm{true}}}{M^i}\Delta\alpha_j\right)\right]^2}{\left(\sigma_i \frac{M^{i,\mathrm{true}}}{M^i}\right)^2}+\sum_j \frac{\Delta\alpha_j^2}{\sigma_{\alpha_j}^2}$$

Normalisation is clearly relative (multiplicative).

Are the other systematics errors additive or multiplicative ? Debatable !

Impact is mostly negligible, except at very large Q^2 and x where statistical errors and fluctuations are the largest.

At that stage : an additional uncertainty has been added.

Correlation of systematics between H1 & ZEUS and between data sets of the same experiment ?

Similar methods for detector calbration, MC simulations of HFS DIS and photoproduction background. Some correlations should exist. Have identified 12 possible uncertainties of common origin.

Compare 2^{12} averages taking all pairs as corr & uncorr in turn. Determine average deviations from central values.

→ Mostly negligible except for photoproduction and hadronic energy scale

The sources of procedural errors related to the averaging procedure :

- Center of Mass Energy correction (at the per mille level but up to 5 % at large y, Q2 ~ 10 GeV^2)

- Multiplicative vs additive systematic errors (< 1 % except at large x, large Q^2)

- Correlations between experiments :

  Subtraction of photoproduction background assumed to be correlated in H1-ZEUS (1 - 2% at large y)

  Hadronic energy scale (1% at low y)

are added to the averaged data points. They are at the few permille level across most of kinematic plane with few exceptions.