Probing QCD at the Highest Q^2 Deep-Inelastic Scattering

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Physics In Collision
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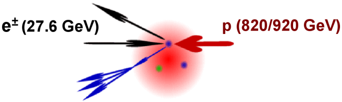
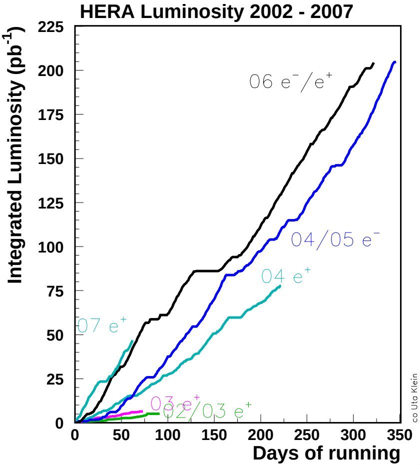
Kobe, Japan

On behalf of the ZEUS and H1 Collaborations

At HERA $e^{\pm}$ were collided with protons at the interaction points of H1 and ZEUS with $\sqrt{s} \approx 320$ GeV

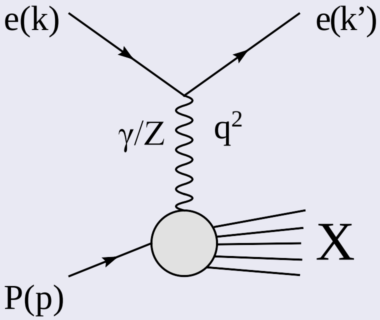




HERA I: ZEUS $\mathcal{L} \sim 130\ \mathrm{pb}^{-1}$

HERA II: ZEUS $\mathcal{L} \sim 360\ \mathrm{pb}^{-1}$

Neutral Current (NC)



Similar diagrams involving W exchange for Charged Current scattering (CC)

Kinematics

4-momentum transfer:

$$q = k - k'$$

Virtuality (resolving power):

$$Q^2 = -q^2$$

Parton momentum fraction:

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

e Inelasticity:

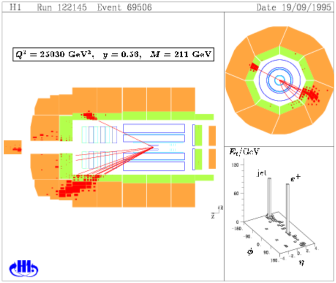
$$y = \frac{q.p}{k.p}$$

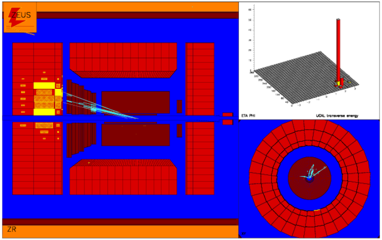
(CM energy)^2:

$$s = (k+p)^2 \approx 4E_e E_p$$

γP CM energy/M_X:

$$W = (p+q)^2$$





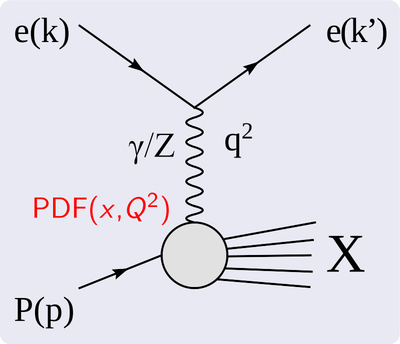
H1

- Liquid Argon Calorimeter
- Optimised for precision measurement of the scattered lepton

ZEUS

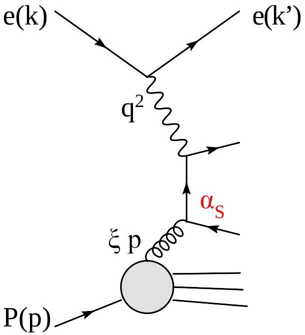
- Depleted Uranium Calorimeter
- Optimised for precision measurement of the hadronic final state

HERA was the premier machine for measuring structure functions and hence the parton distribution functions (PDFs) of the proton:



Scaling violations of structure functions give sensitivity to α_S

- Proton beam → no need for nuclear corrections
- Different E_P data sets allow F_L measurement
- Electron beam → cleaner than PP or $P\bar{P}$
- e^+/e^- data taking can exploit EW effects
- Several orders of magnitude reach in Q^2, x

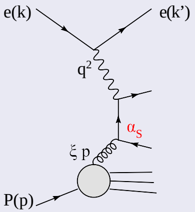


In DIS charm and beauty production comes mainly from BGF (Analogous with flavour creation processes in hadron-hadron collisions). One can measure the structure functions $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ by tagging events via:

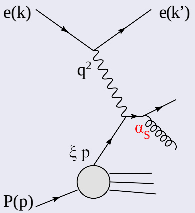
- Impact Parameter
- D meson production
- semileptonic heavy quark decays

This gives sensitivity to the gluon PDF

Boson-Gluon Fusion



QCD Compton



The *eP* environment is excellent for jet physics.

- Jets are copiously produced at HERA.
- Minimal contribution from underlying event (at High Q^2)

k_T algorithm is the algorithm of choice at HERA

- Sensitivity to α_S in jet production cross sections
- Sensitivity to $g(x, Q^2)$ in cross sections
- Possibility of studying jet substructure

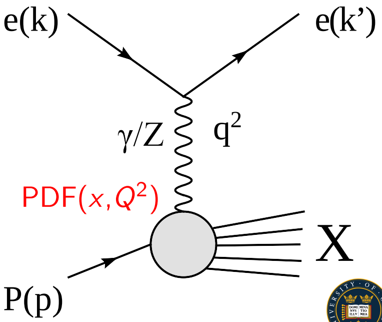
NC Double Differential Cross-Section

$$\frac{\mathrm{d}^2\sigma_{NC}^{e^{\pm}p}}{\mathrm{d}x\mathrm{d}Q^2} = \frac{2\pi\alpha^2 Y_+}{xQ^4}[F_2^{NC}(x,Q^2) - \frac{y^2}{Y_+}F_L^{NC}(x,Q^2) \mp \frac{Y_-}{Y_+}xF_3^{NC}(x,Q^2)]\,(1+\delta_r)$$

$$\frac{\mathrm{d}^2\sigma_{NC}^{e^{\pm}p}}{\mathrm{d}x\mathrm{d}Q^2} = \frac{\mathrm{d}^2\sigma_{NC,\mathrm{Born}}^{e^{\pm}p}}{\mathrm{d}x\mathrm{d}Q^2}(1+\delta_r)$$

$$Y_{\pm} = 1 \pm (1-y)^2$$

δ_r Electroweak radiative correction



Structure Functions

		LO QCD
F_2	Dominates most phase space	$\sum x(q_i + \bar{q}_i)$
xF_3	Parity violating (high Q^2)	$\sum x(q_i - \bar{q}_i)$
F_L	Longitudinal SF (high y)	0

From scaling violations:

$$F_L \approx \alpha_s xg(x,Q^2)$$

CC Double Differential Cross-Section

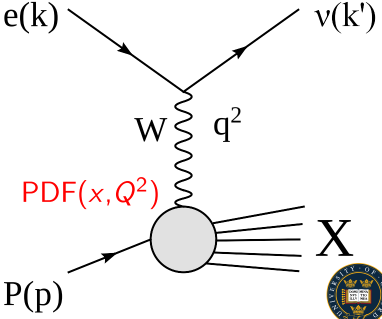
$$\frac{d^2\sigma^{e^\pm p}_{CC}}{dx dQ^2} = \frac{G_F^2 M_W^2}{4\pi x(Q^2+M_W^2)^2}[Y_+ F_2^{CC}(x,Q^2) - y^2 F_L^{CC}(x,Q^2) \mp Y_- xF_3^{CC}(x,Q^2)]\,(1+\delta_r)$$

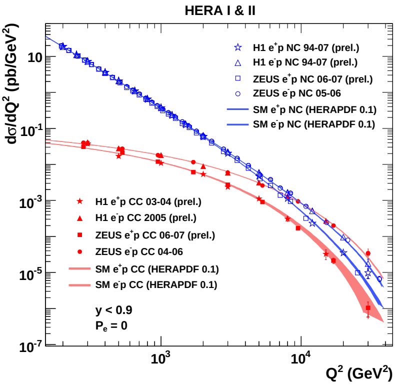
Structure Functions

$$F^{CC}_{2,e^+} = x(d + s + \bar{u} + \bar{c})$$
$$xF^{CC}_{3,e^+} = x(d + s - \bar{u} - \bar{c})$$
$$F^{CC}_{2,e^-} = x(u + c + \bar{d} + \bar{s})$$
$$xF^{CC}_{3,e^-} = x(u + c - \bar{d} - \bar{s})$$

Reduced Cross Sections

$$\tilde{\sigma}^{CC}_{e^+} = x[(1-y)^2(d+s) + \bar{u} + \bar{c}]$$
$$\tilde{\sigma}^{CC}_{e^-} = x[(1-y)^2(\bar{d}+\bar{s}) + u + c]$$



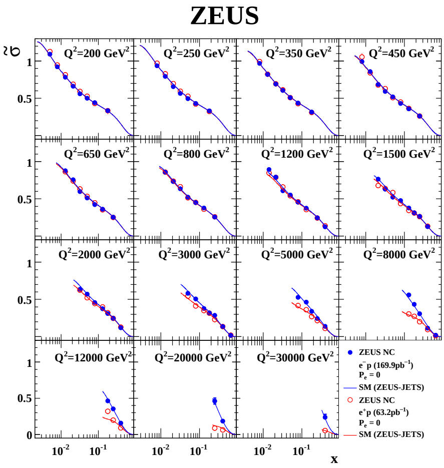


ZEUS-prel-09-001

Differential cross section well described by SM

- NC cross section much larger at lower Q^2
- CC and NC similar for $Q^2 \approx M_V^2$
- Differences in e^+p and e^-p CC from PDFs
- Differences in e^+p and e^-p NC from EW effects

There are also also data subsets with longitudinally polarised $e^\pm$ beams



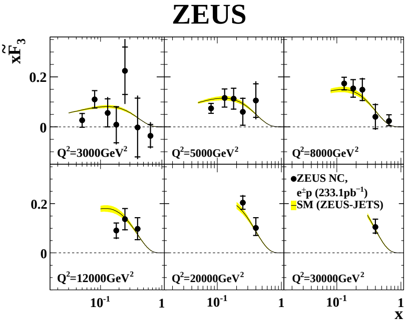
More important for PDF fitting are the reduced cross sections.

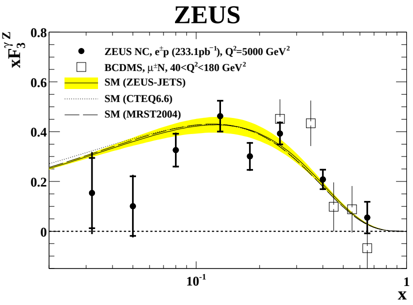
- Well described by SM prediction
- HERA II e^-p sample $10\times$ HERA I lumi
- Can now obtain much more precise xF_3 from $e^{\pm}p$ difference

Eur. Phys. J. C62 (2009) 625

xF_3

$$xF_3 \propto \sum x(q_i - \bar{q}_i)$$





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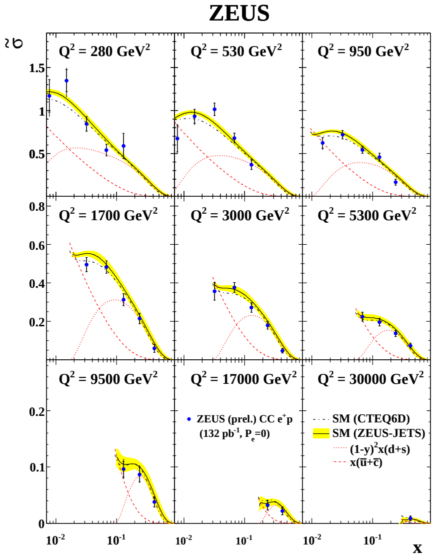
CC σ



New measurements of CC DIS cross sections have been performed:

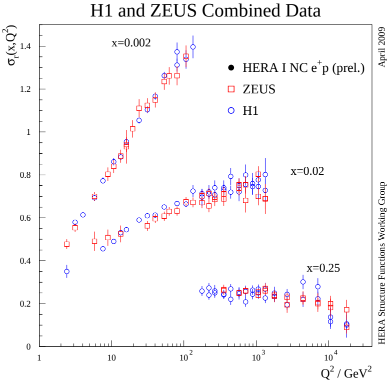
- Large e^-p sample (Eur. Phys. J. C61 (2009) 223)
- Large new e^+p sample (ZEUS-prel-09-002)

The flavour selecting properties of the charged exchange mean that e^+p data is particularly useful for constraining the d PDF.

In addition to new data, considerable progress has been made in combining results made using the data collected from 1994-2000.

Strategy:

- Swim measurements to common x, Q^2 grid
- Correct data to same E_p (920 GeV)
- Calculate average values and uncertainties[a] using a global combination
- Evaluate procedural uncertainties



[a] arXiv:0904.0929

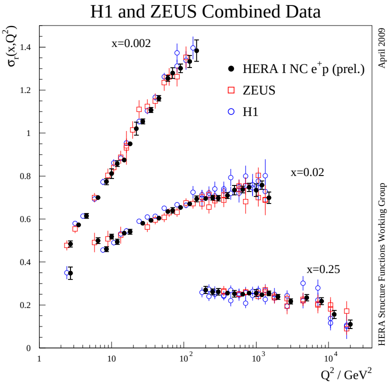
1402 points combined to 741 unique measurements

- $\chi^2/\text{ndf} = 637/656$
- 110 systematic uncertainties from experiments
- 3 systematic uncertainties from combination

Overall precision is improved:

- $3 < Q^2 < 500\,\text{GeV}$ 2% precision
- $20 < Q^2 < 100\,\text{GeV}$ 1% precision

H1prelim-09-045,ZEUS-prel- 09-011



Recall that for unpolarised $e^{\pm}p$ scattering:

$$\frac{\mathrm{d}^2\sigma^{e^{\pm}p}}{\mathrm{d}x\mathrm{d}Q^2} = \frac{2\pi\alpha_2}{xQ^4}[Y_+F_2(x,Q^2) - y^2F_L(x,Q^2) \mp Y_{\mp}xF_3(x,Q^2)]$$

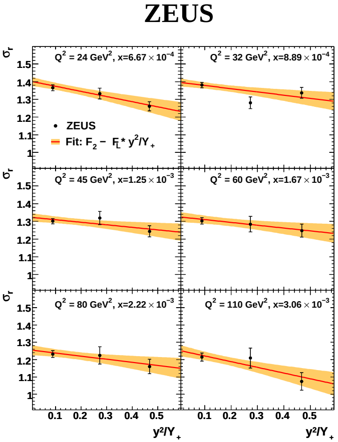
For now we can neglect xF_3 and write an expression of the reduced cross section (σ_r)

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

for F_L Measurements at different y for the same x, Q^2 required.
Solution? Use different beam energies
Choice of energies is made to maximise difference in $\frac{y^2}{Y_+}$

E_p (GeV)	460	575	920
H1 $\mathcal{L}$ (pb^{-1})	12	6	22
ZEUS $\mathcal{L}$ (pb^{-1})	14	7	44

- The first direct measurements of F_L have now been published[a].
- In addition H1 have produced a new measurement[b] in an extended Q^2 range: $2.5 < Q^2 < 800\,\mathrm{GeV}$
- For $Q^2 > 10\,\mathrm{GeV}$ measurement in good agreement with pQCD



[a] Phys. Lett. B665 (2008) 139, DESY-09-046
[b] H1prelim-09-044

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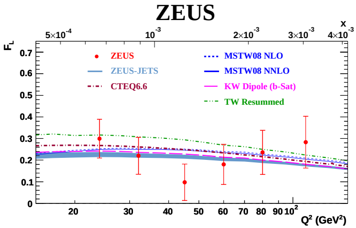

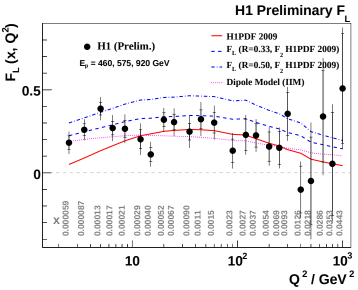

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[a] Phys. Lett. B665 (2008) 139, DESY-09-046

[b] H1prelim-09-044

Both H1 and ZEUS have performed their own PDF fits.

Analysis is made using the DGLAP equations:

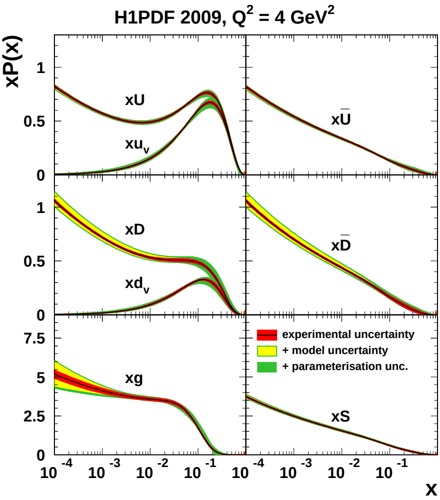
DGLAP Equations

$$\frac{\partial q_i(x,\mu^2)}{\partial \ln \mu^2} = \frac{\alpha_s(\mu^2)}{2\pi} \int_x^1 \frac{dz}{z} \left(\sum_j P_{q_i q_j} \cdot q_j(\frac{x}{z},\mu^2) + P_{q_i g} \cdot g(\frac{x}{z},\mu^2) \right)$$

$$\frac{\partial g_i(\frac{x}{z},\mu^2)}{\partial \ln \mu^2} = \frac{\alpha_s(\mu^2)}{2\pi} \int_x^1 \frac{dz}{z} \left(\sum_j P_{g q_j} \cdot q_j(\frac{x}{z},\mu^2) + P_g \cdot g(\frac{x}{z},\mu^2) \right)$$

The DGLAP equations tell us the PDF(Q^2,x) given PDF(Q_0^2,x)

In addition a new PDF fit to the combined data (HERAPDF) has been made.



New H1 fit[a] uses only H1 data:

Data Set		Data Points	χ^2_{unc}
low Q^2	[2]	58	55.9
medium Q^2	this measurement	99	81.5
e^+p NC high Q^2, 94 – 97	[7]	130	92.6
e^+p CC high Q^2, 94 – 97	[7]	25	21.2
e^-p NC high Q^2, 98 – 99	[8]	139	112.1
e^-p CC high Q^2, 98 – 99	[8]	28	17.3
e^+p NC high Q^2, 99 – 00	[9]	147	137.4
e^+p CC high Q^2, 99 – 00	[9]	28	31.1

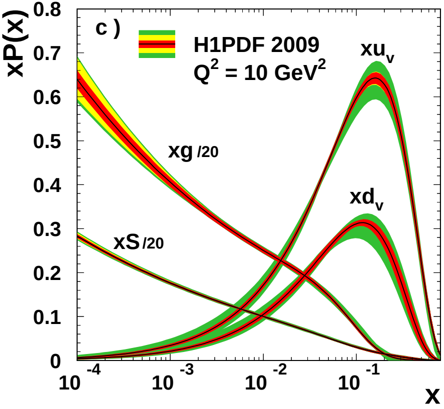
Fits 5 PDFs : $xu_v, xd_v, xg,$
$x\bar{U} = \bar{u} + \bar{c},\ x\bar{D} = \bar{d} + \bar{s} + \bar{b}$

[a] DESY-09-005

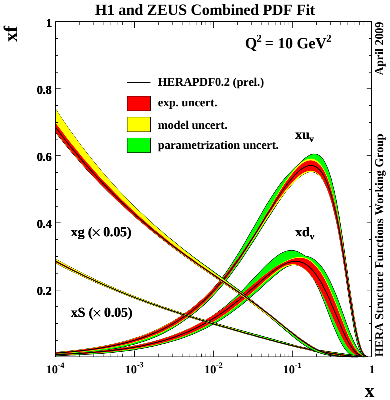
- Good fit to the data $\chi^2/n.d.f = 587/644$
- Reduced uncertainty at low-x w.r.t. H1PDF2000
- Larger (more realistic) uncertainties at high-x (new parametrisation uncertainty dominant)

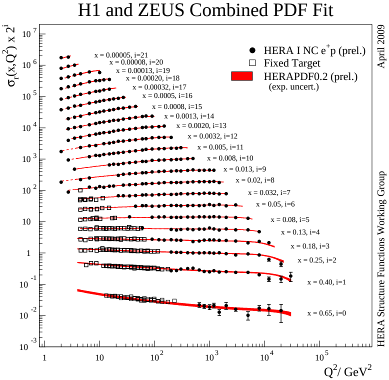
Parametrisation Uncertainty

New uncertainty determined by using parametrisations which describe data well but have unphysical behaviour at large x



Similar procedure adopted for fit to combined HERA data[1]:

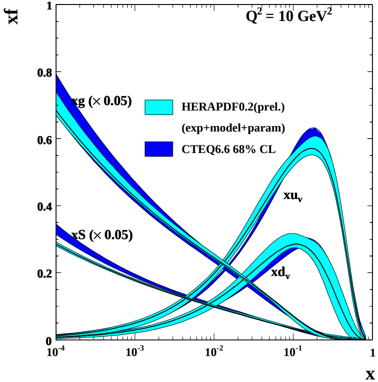


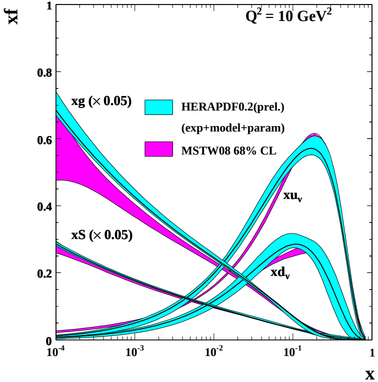


A beautiful fit to the data: $\chi^2/n.d.f. = 576/592$

[1] H1prelim-09-045,ZEUS-prel- 09-011

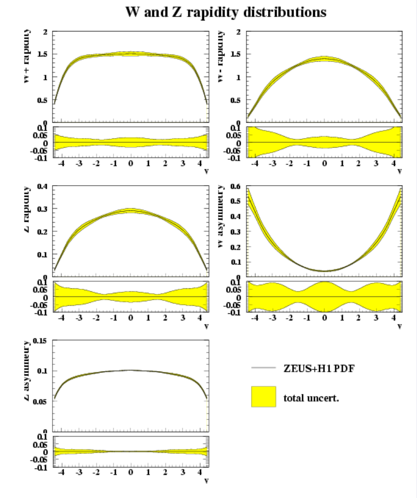
The new combined HERA-I fit compares well with global fits:



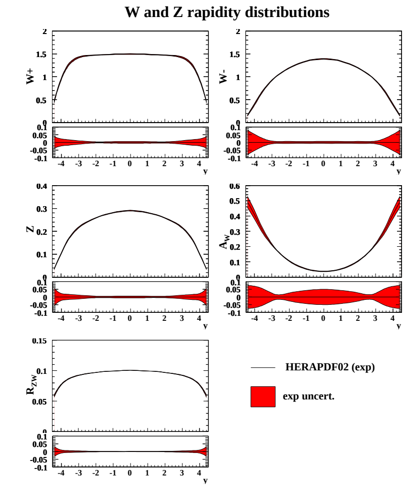


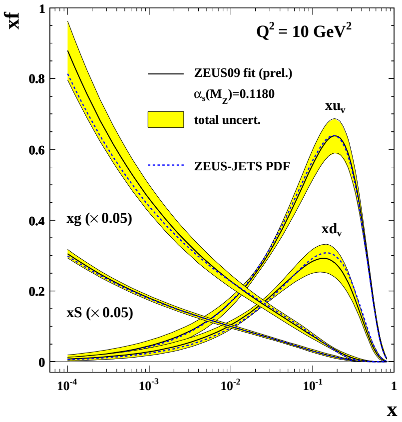
This has implications for the LHC

ZEUS-S: ZEUS + H1



HERA PDF





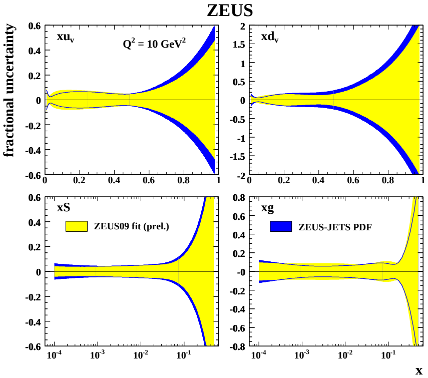
ZEUS-prel-09-010

ZEUS-Jets showed that adding jet data constrains the gluon better.
New ZEUS fits show areas of improvement with HERA II data.
Added data relative to ZEUS-jets:

- High Q^2 e^-p NC
- High Q^2 e^-p CC
- High Q^2 e^+p CC
- F_L measurement

1060 points with $\chi^2/n.d.f. = 0.97$
Polarised data treated separately $\rightarrow$ EW sensitivity

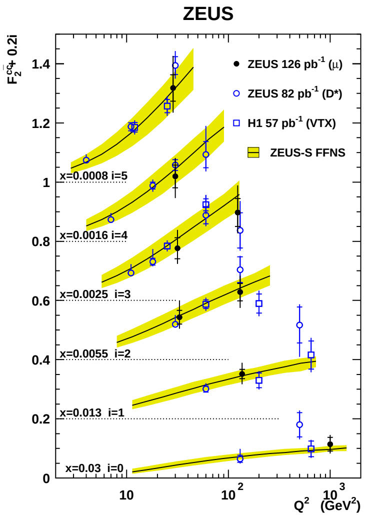
New ZEUS Fit



Comparison of uncertainties on new fit to ZEUS-JETS shows areas of improvement from adding HERA II data:

- Better u_V at high-x from Highest Q^2 e^-p NC and CC data
- Better d_V at high-x from Highest Q^2 e^+p CC data
- Better g from F_L data

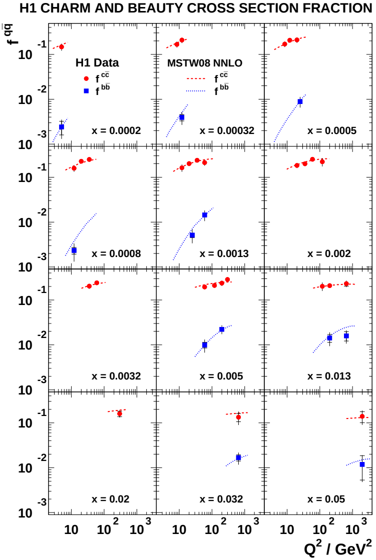
$F_2^{Q\bar{Q}}$



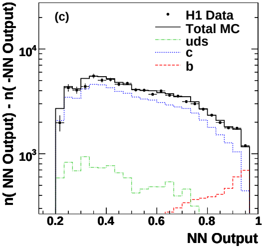
A new measurement[a] of $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ using muons to tag events.

- Results for $F_2^{c\bar{c}}$ shown here
- Results agree well with QCD predictions
- Agree well with measurements from D^* events and inclusive impact parameter measurements

[a] DESY-09-056

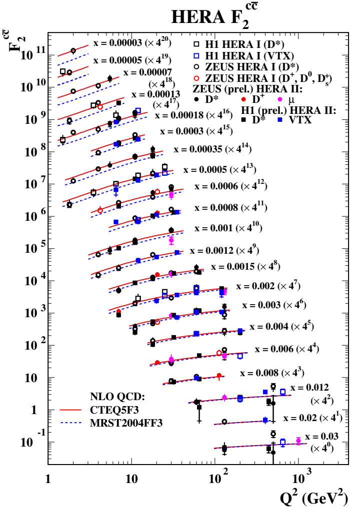


New measurement[a] of $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ (inclusive impact parameters)

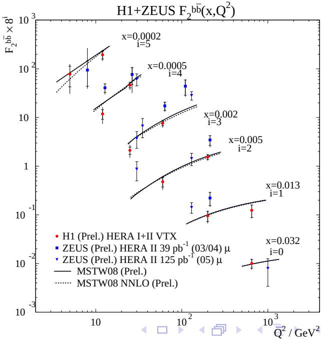


- Smallest extrapolation to $F_2^{Q\bar{Q}}$
- Agrees well with QCD predictions

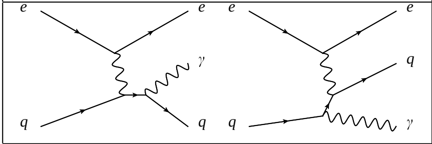
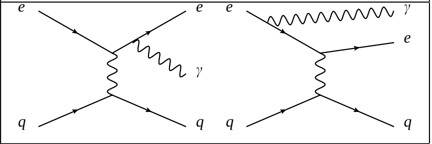
[a] DESY-09-096



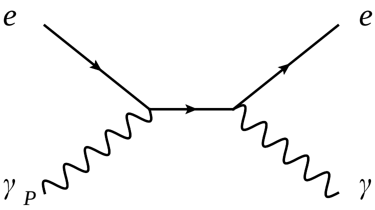
- Detailed, consistent picture of $F_2^{Q\bar{Q}}$ has been built up
- Many independent measurements of $F_2^{c\bar{c}}$
- Still much to learn about $F_2^{b\bar{b}}$



Isolated γs at HERA produced via:

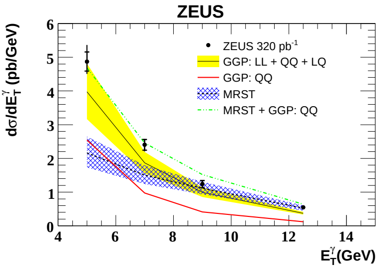
Quark Line (QQ)	Lepton Line (LL)
	

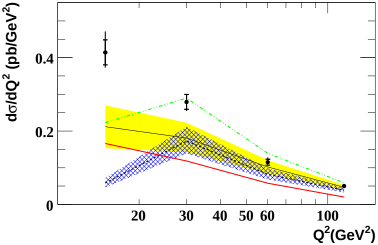
As a consequence of adding QED corrections to the PDFs[2] a photon component γ_P of the PDFs arises. Giving also $e\gamma_P \rightarrow e\gamma$



- $\gamma_P(Q^2, x)$ important for EW corrections at LHC
- MRST2004 the only PDF with full QED corrections
- Used old ZEUS data to cross check γ_P PDF

[2] Eur. Phys. J. C39, No. 2. (2005), 155





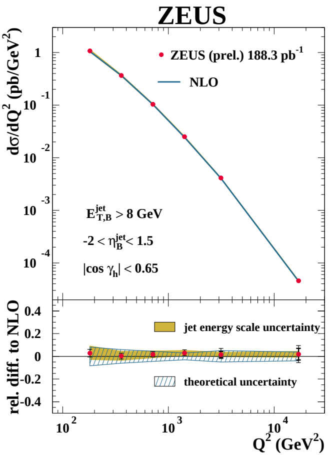
New measurement of isolated photon production at ZEUS:

- Compared to GGP[a]
- Also compared to MRST2004 prediction (LL component only)
- Finally (green line) compared to MRST2004 LL and GGP QQ

E_T spectrum well described by theories, but problems with Q^2 spectrum. (Similar behaviour w.r.t to GGP previously observed by H1)

MSTW08 with QED corr. in preparation

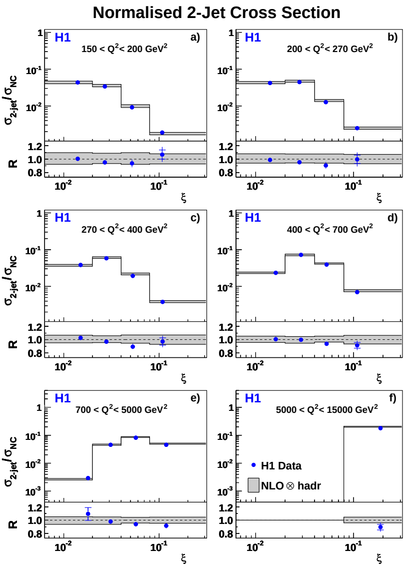
[a] Gehrman-De Ridder et al. - Phys. Rev. Lett.96:132002 (2006)



Inclusive jets in High Q^2 NC[a]:

- A stringent test of pQCD
- Good description by NLO QCD over large Q^2 range
- Theoretical uncertainty dominates experimental uncertainty at high Q^2
- In some regions PDFs the dominant theoretical uncertainty $\rightarrow$ can constrain the gluon

[a] ZEUS-prel-09-006



New H1 inclusive and multijet measurement [a]:

- momentum fraction carried by incoming parton:

$$\zeta = x_{\mathrm{Bj}}(1 + \frac{M_{12}}{Q^2})$$

- Normalised dijet cross sections as a function of ζ
- NLO cross sections describe data well
- Theory error (Higher orders) significantly larger than exp.

[a] DESY-09-032

From H1 multijet paper:

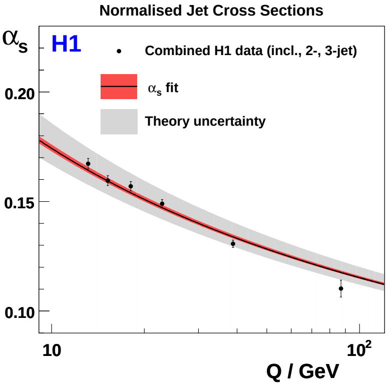
Extraction of α_s

- QCD predictions were fitted using a χ^2 method
- Values of α_s were extracted by fitting the individual normalized inclusive, 2-jet, 3-jet cross sections and their combination

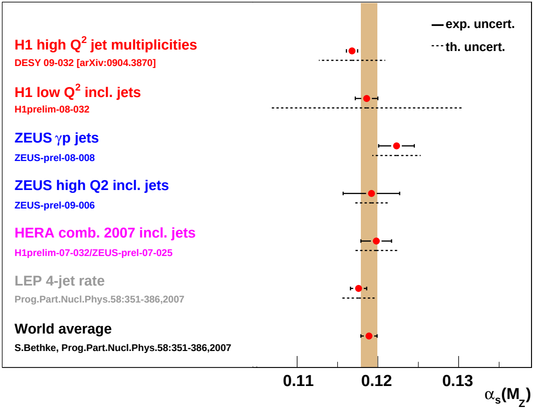
Fit quality $\chi^2/n.d.f. = 65/53$

DESY-09-032

See the poster by A. Baghdasaryan



Observed running of α_s as expected from QCD



- Extracted values of α_s compatible with world average
- Comparable precision to e^+e^- measurements
- Different measurements, environments and processes consistent

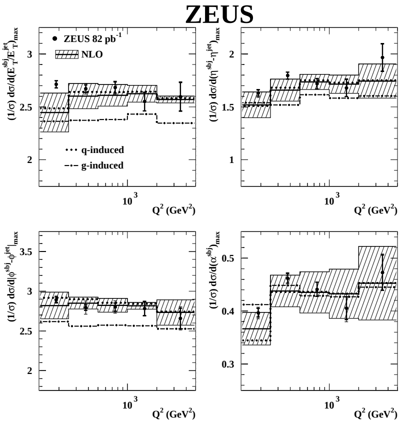
Great success of QCD!
More HERA jet measurements to be seen in K. Hatakeyama's talk

Jet substructure can be studied by re-running the k_T algorithm with smaller values of the resolution parameter $y_{\rm cut}$
Subjet distributions can be used to study:

- Pattern of radiation from the primary parton
  - Direct test of the splitting functions and scale dependence
- Colour coherence
  - soft radiation tends to be emitted in the proton direction

As attention at the LHC turns to jet-substructure as tool for boosted-heavy particle reconstruction[3] it is very interesting to see theory confront real data on jet substructure.

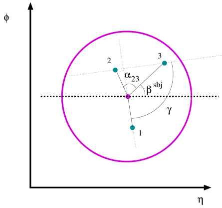
[3] Phys.Rev.Lett.100:242001,2008

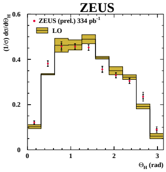


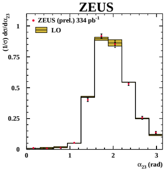
Study of jets with exactly two subjets for $y_{cut} = 0.05$[a]

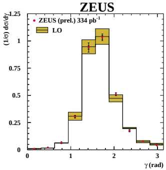
- Normalised cross sections well described by pQCD predictions
- Scale dependence of radiation from partons well described by pQCD

[a] DESY-08-178









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Subjet distributions for jets with 3 subjets for $y_{\mathrm{cut}} = 0.03$

- θ_H - angle between planes determined by the highest E_T subjet and the beam and the two lowest E_T subjets
- α_{23} - The angle between the highest E_T subjet and the vector difference of the two lowest E_T subjets as seen from the jet center in the $\eta - -\phi$ plane
- γ - The angle between the highest E_t subjet and the vector difference of the two lowest E_T subjets

pQCD predictions give an adequate description of the data

1 Introduction

2 Structure Functions and Parton Distribution Functions

3 Jets

4 Summary

HERA continues to produce important QCD measurements:

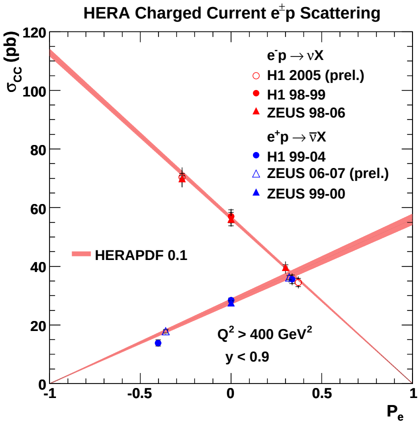
- World leading proton structure determination:
  - New data at highest Q^2 will help constrain valence PDFs
  - $F_2^{Q\bar{Q}}$ with increasing precision
  - Potential to measure photon component of the proton
  - New combined data even more precise than using separate results
- Precise measurements of α_S
- Excellent determination of jet cross sections:
  - Theoretical uncertainties often larger than experimental
  - Potential to constrain the gluon PDF

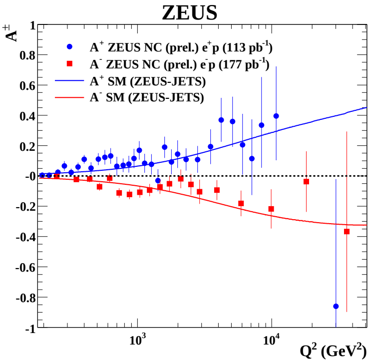
Back-Up Slides begin here

5 EW results

6 Combination and PDF fits

Total CC Cross section





ZEUS-prel-07-012
ZEUS-prel-08-005

With polarised $e^{\pm}$ we now have access to Polarisation asymmetries:

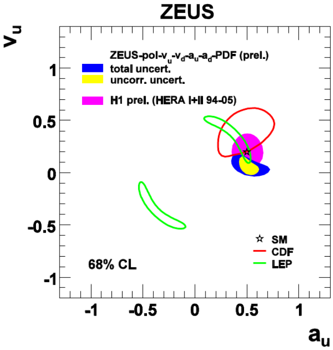
$$A^{\pm} = \frac{2}{\mathcal{P}_R - \mathcal{P}_L} \cdot \frac{\sigma^{\pm}(\mathcal{P}_R) - \sigma^{\pm}(\mathcal{P}_L)}{\sigma^{\pm}(\mathcal{P}_R) + \sigma^{\pm}(\mathcal{P}_L)}$$

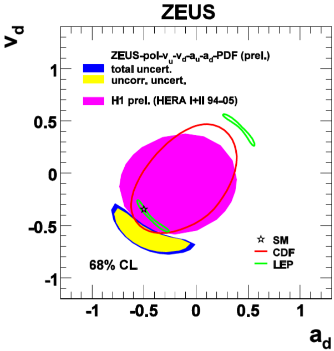
to a good approximation:

$$A^{\pm} \simeq \mp k a_e \frac{F_2^{\gamma Z}}{F_2}$$

at large Bjorken-x

$$A^{\pm} \simeq \mp - k \frac{1 + d_v/u_v}{4 + d_v/u_v}$$





Uses only the preliminary version of the new $e^- p$ NC data

Non ZEUS sources:

- F_2 data on $\mu - p$ scattering from BCDMS [39], NMC [40], and E665 [41];
- deuterium-target data from NMC [40] and E665 [41]. These were included in order to have $\bar{u}$, $\bar{d}$ flavour separation;
- NMC data on the ratio F_2^D/F_2^p [42]. These determine the ratio of the d to u valence shapes;
- the CCFR [43] xF_3 data, from (anti-)neutrino interactions on an iron target. These give the strongest constraint on high-x valence PDFs. They are used only in the x range $0.1 \leq x \leq 0.65$ in order to minimize dependence on the heavy-target corrections. The latter were performed according to the prescription of MRST [31]. These xF_3 data are unaffected by the recent re-analysis of CCFR F_2 data [44, 45].