IL NUOVO CIMENTO Vol. 32 C, N. 5-6 Settembre-Dicembre 2009
DOI 10.1393/ncc/i2010-10529-9

Colloquia: LaThuile09

QCD studies at HERA

D. Traynor(*)(**)

Queen Mary, University of London - Mile End Road, London, E1 4NS, UK

(ricevuto il 10 Novembre 2009; pubblicato online il 18 Gennaio 2010)

Summary. — This article presents a summary of recent results on QCD from HERA. Including; new neutral current and charged current measurements from H1 and ZEUS from the lowest to the highest Q^2, new combinations of both H1 and ZEUS published HERAI data and corresponding PDF fits, the first measurements of F_L, and the extraction of α_s from jet measurements.

PACS 12.38.Qk – Experimental tests.

1. – New deep inelastic scattering results from HERA

Both H1 and ZEUS have recently released new results of the inclusive ep cross-sections covering a kinematic range in Q^2 ($0.2 < Q^2 < 50000\,\text{GeV}^2$) and Bjorken x ($5 \times 10^{-6} < x < 0.65$). The inclusive ep deep inelastic scattering (DIS) cross-section can be expressed in terms of the two structure functions, F_2 and F_L, as

$$\sigma_r(x, Q^2, y) = \frac{\mathrm{d}^2\sigma}{\mathrm{d}x\mathrm{d}Q^2}\frac{Q^2 x}{2\pi\alpha^2 Y_+} = F_2(x, Q^2) - \frac{y^2}{Y_+}F_L(x, Q^2),$$

where Q^2 is the virtuality of the exchanged boson, the Bjorken x is, in the rest frame of the incident proton, the fraction of the proton momentum entering the hard interaction and the inelasticity y is the fraction of the electrons energy that the virtual photon carries. Two types of DIS cross-sections are measured, neutral current which involves the exchange of a virtual photon or Z-boson ($ep \to eX$), and charged current which is mediated by the exchange of a W-boson ($ep \to \nu_e X$).

(*) On behalf of the H1 and ZEUS Collaborations.
(**) E-mail: d.traynor@qmul.ac.uk

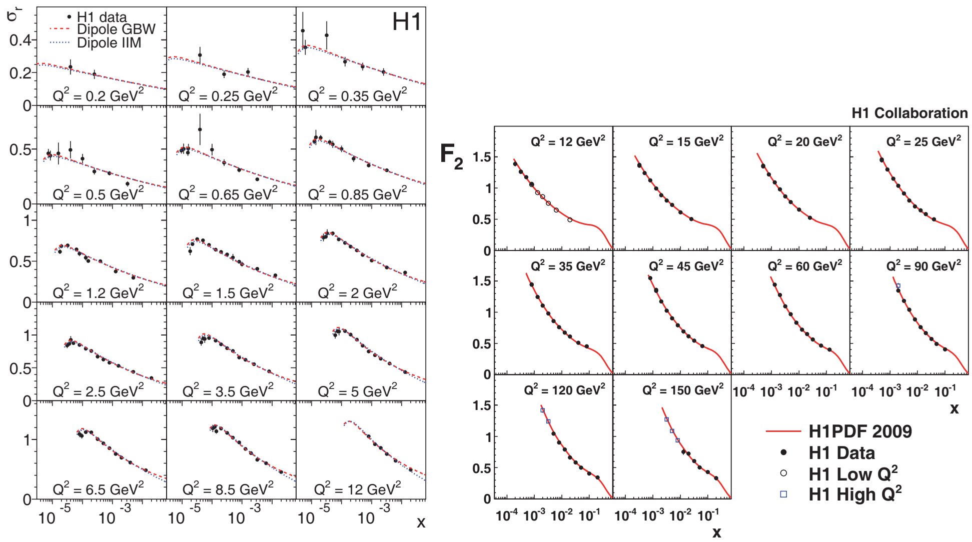

Fig. 1. – Left: reduced cross-section σ_r, from the combined low-Q^2 H1 data, as a function of x for fixed Q^2 intervals compared to the GBW and IIM models. The errors represent the statistical and systematic uncertainties added in quadrature. Right: measurement of the structure function F_2 at medium Q^2, as a function of x for fixed Q^2 intervals. The error bars represent the total measurement uncertainties. The curve represents the H12009 QCD fit.

1˙1. *Low-Q^2 neutral current.* – A measurement of the inclusive *ep* scattering cross-section in the region of low momentum transfers, $0.2\,\text{GeV}^2 \le Q^2 \le 12\,\text{GeV}^2$, and low Bjorken x, $5 \times 10^{-6} < x < 0.02$ has been published by H1 [1]. The result is based on two data sets collected in dedicated runs by the H1 Collaboration at HERA at beam energies of 27.6 GeV and 920 GeV for positrons and protons, respectively. A combination with data previously published by H1 leads to a cross-section measurement of a few percent, $\sim 2\%$ accuracy in a large part of the phase space. A kinematic reconstruction method exploiting radiative *ep* events extends the measurement to lower Q^2 and larger x.

For the region $Q^2 \simeq 1\,\text{GeV}^2$, in which the transition from photoproduction to DIS takes place, the data as presented are the most precise result of the H1 Collaboration. The data have been compared to theoretical models which apply to the transition region from photoproduction to deep inelastic scattering. The Colour Dipole Model (CDM) predicts both structure functions F_2 and F_L using a single characteristic dipole scattering cross-section. In fig. 1, left, the data are compared to two versions of the CDM, the GBW model [2] and the IIM model [3], which are found to generally describe the cross-section data well.

1˙2. *Medium-Q^2 neutral current.* – A new measurement of the inclusive double differential cross-section for deep inelastic positron proton scattering in the region of small Bjorken x, $2 \times 10^{-4} \le x \le 0.1$, and four-momentum transfer squared, $12\,\text{GeV}^2 \le Q^2 \le 150\,\text{GeV}^2$ has been made by H1 [4] with beam energies of $E_e = 27.6\,\text{GeV}$ and $E_p = 920\,\text{GeV}$. A small bias in a similar previously published data set, taken at $E_p = 820\,\text{GeV}$, is found and corrected. The two data sets are then combined and represent the most precise measurement in this kinematic region to date, with typical total uncertainties in the range of 1.3–2% and includes all H1 HERAI data.

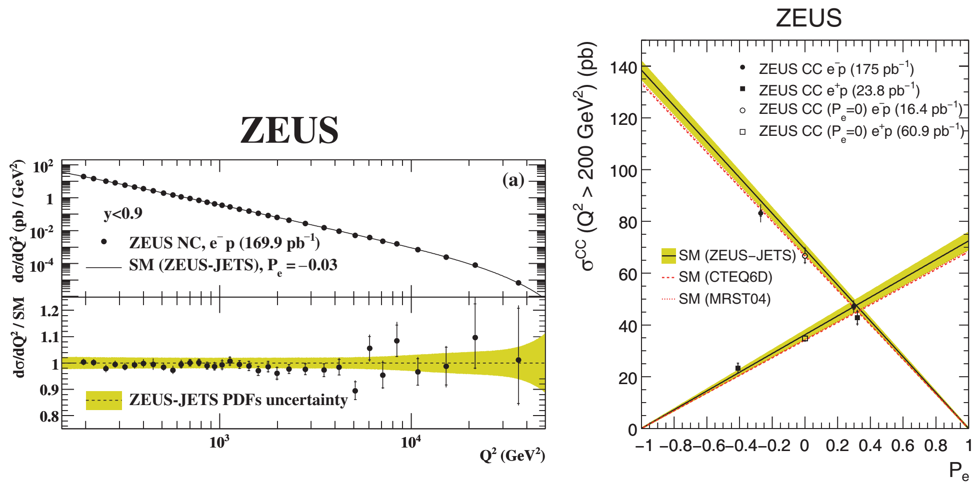

Fig. 2. – Left: the e^-p NC DIS cross-sections $\mathrm{d}\sigma/\mathrm{d}Q^2$ for $y < 0.9$ and the ratio to the SM prediction. The closed circles represent data points in which the inner error bars show the statistical uncertainty while the outer bars show the statistical and systematic uncertainties added in quadrature. The curves show the predictions of the SM evaluated using the ZEUS-JETS PDFs, the shaded band shows the uncertainties from the fit. Right: the total cross-sections for e^-p and e^+p CC DIS as a function of the longitudinal polarisation of the lepton beam. The lines show the predictions of the SM evaluated using the ZEUS-JETS, CTEQ6D and MRST04 PDFs. The shaded bands show the experimental uncertainty from the ZEUS-JETS PDF.

The kinematic range of the measurement corresponds to a wide range of inelasticity y, from 0.005 to 0.6. The data are used to determine the structure function $F_2(x, Q^2)$, which is observed to rise continuously towards low x at fixed Q^2, fig. 1, right. An NLO QCD fit to the H1 data alone, including the new medium-Q^2 data, is also shown. The fit implements a variable flavour treatment of heavy quark threshold effects. This new H1PDF 2009 fit supersedes the H1PDF 2000 previously obtained and provides a new determination of the gluon and quark densities of the proton including experimental, model, and parameterisation uncertainties.

1˙3. *High-Q^2 neutral current.* – Measurements of the neutral-current cross-sections for deep inelastic scattering in e^-p collisions at HERA with a longitudinally polarised electron beam have been published by ZEUS [5]. The single differential cross-sections $\mathrm{d}\sigma/\mathrm{d}Q^2$ (fig. 2, left), $\mathrm{d}\sigma/\mathrm{d}x$ and $\mathrm{d}\sigma/\mathrm{d}y$ and the double-differential cross-sections in Q^2 and x are measured in the kinematic region $y < 0.9$ and $Q^2 > 185\,\mathrm{GeV}^2$ for both positively and negatively polarised electron beams and for each polarisation state separately.

The measurements are based on an integrated luminosity of $169.9\,\mathrm{pb}^{-1}$ taken with the ZEUS detector in 2005 and 2006 at a centre-of-mass energy of $318\,\mathrm{GeV}$. The structure functions $x\tilde{F}_3$ and $xF_3^{\gamma Z}$ were also determined by combining the e^-p results with previously measured e^+p neutral-current data. The asymmetry parameter A^- is used to demonstrate the parity-violating effects of electroweak interactions at large spacelike photon virtuality. The measurements agree well with the predictions of the standard model.

1˙4. *Charged current.* – Measurements of the cross-sections for charged-current deep inelastic scattering in ep collisions with a longitudinally polarised electron beam have

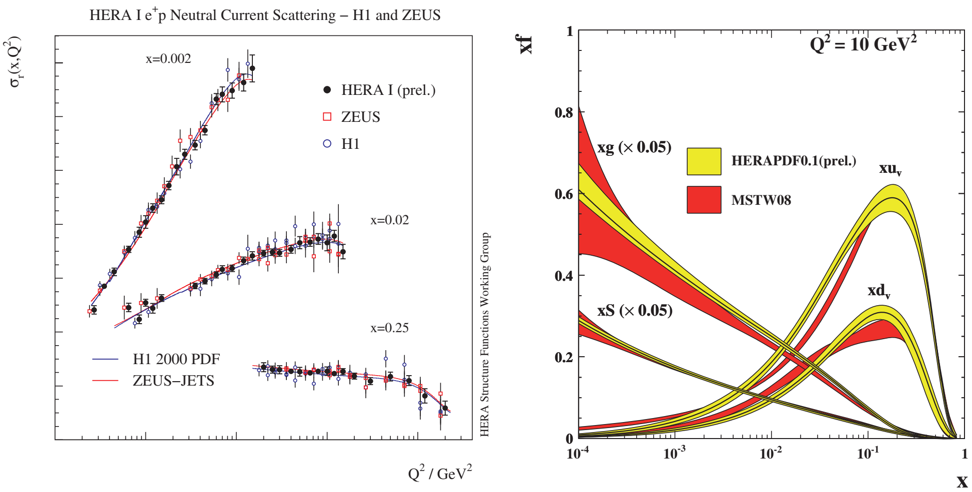

Fig. 3. – Left: deep inelastic neutral-current e^+p scattering cross-section measurements for three selected x bins as a function of Q^2. The H1(open points) and ZEUS data (open squares) are compared to the H1 and ZEUS combined data (closed points). Measurements from the individual experiments have been shifted for clarity. The error bars show the total uncertainty. The curves are NLO QCD fits as performed by H1 and ZEUS to their own data. Right: HERA PDFs at $Q^2 = 10\,\text{GeV}^2$ compared to the PDFs from MSTW08 (prel.) [8].

been published by ZEUS [6]. The measurements are based on a data sample with an integrated luminosity of $175\,\text{pb}^{-1}$ collected with the ZEUS detector at HERA at a centre-of-mass energy of 318 GeV. Measurements made include; the total cross-section for positively and negatively polarised electron beams, fig. 2, right, the differential cross-sections $\mathrm{d}\sigma/\mathrm{d}Q^2$, $\mathrm{d}\sigma/\mathrm{d}x$ and $\mathrm{d}\sigma/\mathrm{d}y$ for $Q^2 > 200\,\text{GeV}^2$, and the double-differential cross-section $\mathrm{d}^2\sigma/\mathrm{d}x\mathrm{d}Q^2$ in the kinematic range $280 < Q^2 < 30000\,\text{GeV}^2$ and $0.015 < x < 0.65$. The measured cross-sections are compared with the predictions of the standard model and overall are well described by the predictions of the standard model.

2. – HERA data combination and PDF fits

It is possible to improve the precision of the ZEUS and H1 neutral and charged current inclusive cross-sections by combining their published HERAI measurements [7]. This is possible because they are measuring the same physics in a similar kinematic region. These data have been combined using a theory-free Hessian fit in which the only assumption is that there is a true value of the cross-section, for each process, at each x and Q^2 point. Thus each experiment has been calibrated to the other. This works well because the sources of systematic uncertainty in each experiment are rather different, such that all the systematic uncertainties are re-evaluated. The resulting systematic uncertainties on each of the combined data points are significantly smaller than the statistical errors, fig. 3, left.

The combined HERAI data set provides high-precision data, with small systematic uncertainties, across a broad kinematic range such that these data can be used as the sole input for an NLO QCD PDF fit. The data at low x, $x < 0.01$, provide information on the sea and the gluon PDFs, and the high-Q^2 HERA data can be used to determine the valence PDFs. The consistent treatment of systematic uncertainties in the combined data set ensures that experimental uncertainties on the PDFs can be calculated without need for an increased χ^2 tolerance. This results in PDFs with greatly reduced experimental uncertainties compared to the separate analyses of the ZEUS and H1 experiments. Model uncertainties, including those arising from parametrization dependence, have also been carefully considered. The resulting HERAPDFs (called HERAPDF0.1 [9]) have impressive precision compared to the global fits, fig. 3, right.

3. – Longitudinal structure function, F_L

Both H1 [10] and ZEUS [11] have recently released measurements of the longitudinal structure function, F_L. The two proton structure functions F_L and F_2 are of complementary nature. They are related to the $\gamma^* p$ interaction cross-sections of longitudinally and transversely polarised virtual photons, σ_L and σ_T, according to $F_L \propto \sigma_L$ and $F_2 \propto (\sigma_L + \sigma_T)$. Therefore the relation $0 \leq F_L \leq F_2$ holds. In the Quark Parton Model (QPM), F_2 is the sum of the quark and anti-quark x-distributions, weighted by the square of the electric quark charges, whereas the value of F_L is zero. In Quantum Chromodynamics (QCD), the longitudinal structure function differs from zero, receiving contributions from quarks and from gluons. At low x and in the Q^2 region of deep inelastic scattering the gluon contribution greatly exceeds the quark contribution. Therefore F_L is a direct measure of the gluon distribution to a very good approximation. The gluon distribution is also constrained by the scaling violations of $F_2(x, Q^2)$ as described by the DGLAP QCD evolution equations. An independent measurement of F_L at HERA, and its comparison with predictions derived from the gluon distribution extracted from the Q^2 evolution of $F_2(x, Q^2)$, thus represents a crucial test on the validity of perturbative QCD at low Bjorken x.

The measurement of F_L requires several sets of DIS cross-sections at fixed x and Q^2 but at different y. This was achieved at HERA by variations of the proton beam energy whilst keeping the lepton beam energy fixed. The measurement of $F_L(x, Q^2)$ is based on data collected with a positron beam energy of 27.5 GeV and three proton beam energies, 920, 575 and 460 GeV.

The longitudinal structure function is extracted from the measurements of the reduced cross-section as the slope of σ_r *vs.* y^2/Y_+, this procedure is illustrated in fig. 4, left. The measured F_L values agree with higher-order QCD calculations based on parton densities obtained using cross-section data previously measured at HERA, fig. 4, right.

A summary of results from H1 for F_L, averaged in x for a given Q^2, for medium and high Q^2 is shown in fig. 5.

4. – α_s from jets

Jet production in neutral-current (NC) deep inelastic scattering (DIS) at HERA provides an important testing ground for Quantum Chromodynamics (QCD). While inclusive DIS gives only indirect information on the strong coupling via scaling violations of the proton structure functions, the production of jets allows a direct measurement of α_s.

The new HERA combined $\alpha_s(M_Z)$ value is $\alpha_s(M_Z) = 0.1198 \pm 0.0019(\text{exp.}) \pm 0.0026(\text{th.})$ (HERA combined 2007), with an experimental uncertainty of 1.6% and a theoretical uncertainty of 2.2%. In addition, to study the running of the strong coupling, fits of $\alpha_s(M_Z)(\mu_R = E_T)$ for several bins of E_T and integrated over Q^2 were performed. The results are shown in fig. 6, left, compared to the pQCD evolution of $\alpha_s(M_Z)$ from

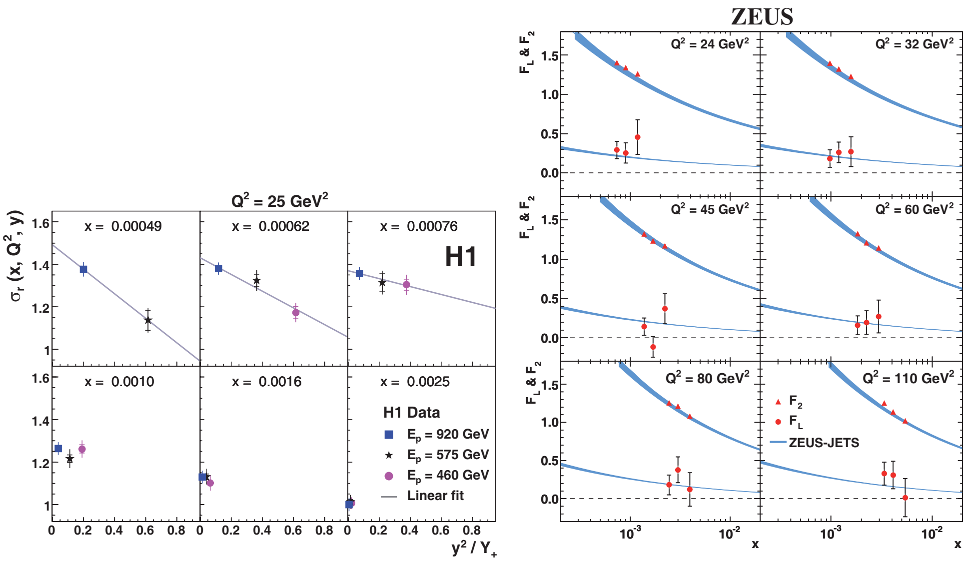

Fig. 4. – Left: the reduced inclusive DIS cross-section plotted as a function of y^2/Y_+ for six values of x at $Q^2 = 25\,\mathrm{GeV}^2$, as measured by H1. The inner error bars denote the statistical error, the full error bars include the systematic errors. The luminosity uncertainty is not included in the error bars. For the first three bins in x, corresponding to larger y, a straight line fit is shown, the slope of which determines $F_L(x, Q^2)$. Right: F_L and F_2 at 6 values of Q^2 as a function of x. The points and triangles represent the ZEUS data for F_L and F_2, respectively. The error bars on the data represent the combined statistical and systematic uncertainties. The error bars on F_2 are smaller than the symbols. A further $\pm 2.5\%$ correlated normalisation uncertainty is not included. The DGLAP predictions for F_L and F_2 using the ZEUS-JETS PDFs are also shown. The bands indicate the uncertainty in the predictions.

the HERA combined 2007 fit. As can be seen in the figure, the running of the coupling from the HERA jet data is in agreement with the prediction of pQCD.

The new HERA combined $\alpha_s(M_Z)$ value is shown in fig. 6, right, together with the values obtained by each collaboration separately, the 2004 HERA average [12], the most recent value from LEP [13] and the 2006 world average [14]. The determinations are consistent with each other and with the world average. The 2004 HERA average, which is the average of many determinations of $\alpha_s(M_Z)$ at HERA, has a very small experimental uncertainty (0.9%), but the theoretical uncertainty is large (4%), since in making that average the sources of theoretical uncertainty were conservatively assumed to be fully correlated. With the new method of combination presented here, no assumption on correlations is made, and a significant reduction on the theoretical uncertainty is achieved by combining observables for which these uncertainties are well under control. Even though the experimental uncertainty of the HERA combined 2007 value is higher than the HERA average 2004, the total uncertainty of the new combined value, 2.7%, is reduced to almost half due to the significant reduction of the theoretical uncertainty. The theory error is dominated by the missing higher orders estimated by the scale uncertainty. A comparison to the most recent value of $\alpha_s(M_Z)$ from LEP, $\alpha_s(M_Z) = 0.1211 \pm 0.0010(\mathrm{exp.}) \pm 0.0018(\mathrm{th.})$, shows that the central values are compat-

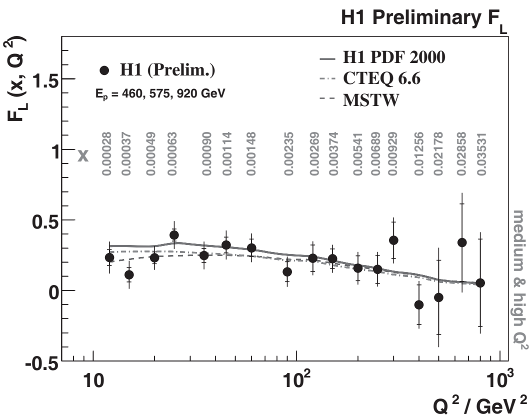

Fig. 5. – (Colour online) The longitudinal structure function F_L averaged in x at a given value of Q^2 in the full range of medium and high Q^2. The resulting x values of the averaged F_L measurements are given in the figure for each point in Q^2. The inner error bars are the statistical errors and the full error bars represent the statistical and systematic errors, added in quadrature. The correlated systematic error between the averaged F_L measurements is estimated to vary between 0.05 and 0.10 in the measured kinematics range. The solid red line represents a QCD prediction based on the H1 PDF2000 fit. The dashed line represents the MSTW and the dash-dotted line the CTEQ6.6 predictions (private communications).

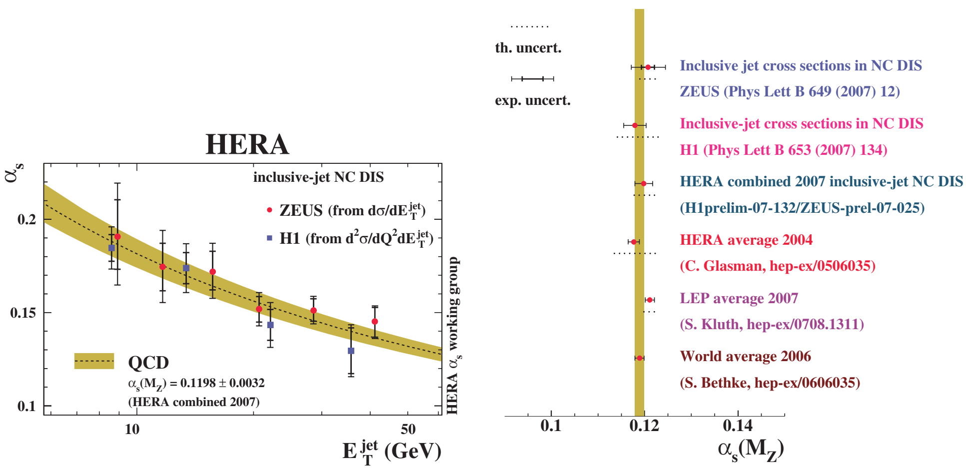

Fig. 6. – Left: results for the fitted values of $\alpha_s(E_T)$ using the inclusive jet cross-sections from H1 and ZEUS. The inner (outer) error bar denotes the experimental (total) uncertainty for each fitted value. The dashed line shows the two-loop solution of the renormalisation group equation evolving the HERA combined 2007 $\alpha_s(M_Z)$, with the band denoting the total uncertainty. Right: determinations of $\alpha_s(M_Z)$ from ZEUS and H1 together with the HERA combined 2007 $\alpha_s(M_Z)$ value. For comparison, the HERA average 2004 and the world average 2006 are also shown. The shaded band represents the uncertainty of the world average.

ible within the experimental uncertainty and that the uncertainty of the HERA combined 2007 value is very competitive with LEP, which includes an average of many precise determinations, such as that coming from τ decays.

REFERENCES

[1] Aaron F. D. *et al.* (H1 Collaboration), *Eur. Phys. J. C*, **63** (2009) 625, hep-ex/0904.0929.
[2] Golec-Biernat K. and Wüsthoff M., *Phys. Rev. D*, **59** (1999) 014017, hep-ph/9807513.
[3] Iancu E., Itakura K. and Munier S., *Phys. Lett. B*, **590** (2004) 199, hep-ph/0310338.
[4] Aaron F. D. *et al.* (H1 Collaboration), *Eur. Phys. J. C*, **64** (2009) 561, hep-ex/0904.3513.
[5] Chekanov S. *et al.* (ZEUS Collaboration), *Eur. Phys. J. C*, **62** (2009) 625, hep-ex/0901.2385.
[6] Chekanov S. *et al.* (ZEUS Collaboration), *Eur. Phys. J. C*, **61** (2009) 223, hep-ex/0812.4620v3.
[7] H1 and ZEUS Collaborations, *Proceedings of the 23rd International Symposium on Lepton and Photon Interactions at High Energy, Daegu, Korea (2007)*, `http://www-h1.desy.de/h1/www/publications/htmlsplit/H1prelim-07-007.long.html`.
[8] Thorne R., private communication.
[9] H1 and ZEUS Collaborations, *Proceedings of the 34th International Conference on High Energy Physics, Philadelphia, USA (2008)*, hep-ex/0809.4946.
[10] Aaron F. D. *et al.* (H1 Collaboration), *Phys. Lett. B*, **665** (2008) 139-146, hep-ex/0805.2809.
[11] Chekanov S. *et al.* (ZEUS Collaboration), *Phys. Lett. B*, **682** (2009) 8, DESY-09-046.
[12] Glasman C., *Proceedings of the 13th International Workshop on Deep Inelastic Scattering, Madison, USA (2005)*, hep-ex/0506035.
[13] Kluth S., in α_s *from LEP*. Talk given at *EPS07, Manchester, England (2007)*, hep-ex/0708.1311.
[14] Bethke S., *Prog. Part. Nucl. Phys.*, **58** (2007) 351.