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Determination of the strong coupling $\alpha_s(M_Z)$ by Combining Inclusive Jet Cross Sections in Deep-Inelastic Scattering at HERA

H1 and ZEUS Collaborations

Abstract

A new combined value of $\alpha_s(M_Z)$ from HERA is presented. This combination is performed using inclusive jet cross-section measurements in neutral current deep-inelastic scattering at high Q^2 recently published by the H1 and ZEUS Collaborations. The method used to obtain the HERA combined 2007 $\alpha_s(M_Z)$ is described. The combined value of $\alpha_s(M_Z) = 0.1198 \pm 0.0019\,(\mathrm{exp.}) \pm 0.0026\,(\mathrm{th.})$ is obtained from these measurements.

1 Introduction

The strong coupling α_s is one of the fundamental parameters of QCD. However, its value is not predicted by the theory and must be determined experimentally. Many precise and consistent determinations of α_s from diverse phenomena, such as from τ decays and from jet rates in e^+e^- annihilation are in excellent agreement with perturbative QCD (pQCD). High precision in the determination of α_s is obtained by using the best available theoretical calculations and by identifying the regions of phase space where both the measurements and the predictions are less affected by uncertainties.

The usual experimental method to determine α_s is to make measurements of observables which are directly sensitive to α_s, and then fit the data using the pQCD predictions with α_s as a free parameter. At HERA, α_s has been determined from many observables which include jet cross sections, jet substructure and structure functions. An overview of jet-related determinations is given in Fig. 1. The determinations of $\alpha_s(M_Z)$ at HERA, most of which come from measurements which involve jet algorithms, show a level of precision competitive with other recent $\alpha_s(M_Z)$ determinations [1].

This paper presents a new $\alpha_s(M_Z)$ value from HERA data on inclusive jet production. The method is based on making a simultaneous fit to H1 and ZEUS data sets, instead of combining $\alpha_s(M_Z)$ values as it was done for the HERA average 2004 analysis [2]. In this way, the correlations in the measurements can be properly treated. For the combination, only those jet measurements from H1 and ZEUS which gave the most precise values of $\alpha_s(M_Z)$ are used, namely the inclusive jet cross sections in neutral current (NC) deep-inelastic scattering (DIS) at high Q^2. Both collaborations have recently published such measurements [3, 4].

2 Fit Procedure

The data sets used in the fit include the inclusive jet double-differential cross sections as a function of the photon virtuality Q^2 and the jet transverse energy E_T from H1 [3] and the inclusive jet single-differential cross section as a function of Q^2 from ZEUS [4]. The fit to extract $\alpha_s(M_Z)$ is done simultaneously to the 30 data points in total: 24 H1 data points for Q^2 between 150 and $15000\,\mathrm{GeV}^2$ and E_T between 7 and $50\,\mathrm{GeV}$ and six ZEUS data points for Q^2 between 125 and $100000\,\mathrm{GeV}^2$.

pQCD predictions of these jet cross sections are calculated as a function of $\alpha_s(M_Z)$ with NLOJET++ [5] using the fastNLO package [6]. A cross check was performed using DISENT [7, 8] instead of NLOJET++, which resulted in compatible values. The factorisation scale μ_f is chosen to be Q and the renormalisation scale μ_r is chosen to be the E_T of each jet. The cross sections are determined using the MRST2001 proton PDFs [9, 10]. Hadronisation correction factors are applied to the calculation as specified in the publications of the data sets. In case of the H1 data the running of the electromagnetic coupling with Q^2 is taken into account in the calculation. This is not done for the ZEUS data, as the cross sections had been corrected to $\alpha_{\mathrm{EM}}(0) = 1/137$ in this case.

Measurements and theory predictions are used to calculate a $\chi^2(\alpha_s(M_Z))$ with the Hessian method, where parameters representing systematic shifts of detector related observables are left free in the fit. The sources of systematic uncertainty are treated as correlated for measurements within one experiment, but as uncorrelated between the two experiments; details are given in the publications of the used data set. It was checked that the model dependence, which in principle could be correlated between experiments, has a negligible effect whether it is treated as correlated or uncorrelated.

The χ^2 function is defined as

$$\chi^2 = \vec{V}^T \cdot M^{-1} \cdot \vec{V} + \sum_k \varepsilon_k^2 \quad ,$$

where the covariance matrix M is composed of contributions from the statistical and uncorrelated systematic errors ($M = M^{\text{stat.}} + M^{\text{uncor.}}$). An element M_{ij} of each of the matrices denotes the covariance between bins i and j. It is noted that $M^{\text{uncor.}}$ is diagonal, while for the present analysis $M^{\text{stat.}}$ is not. The latter is due to the fact that the H1 data are measured differentially in E_T. This, and the presence of multi jet events introduce a statistical correlation between different E_T bins in the same Q^2 bin.

The vector $\vec{V}$ is defined as

$$V_i = \sigma_i^{\text{exp.}} - \sigma_i^{\text{theo.}}(1 - \sum_k \Delta_{ik}\varepsilon_k) \quad ,$$

with $\sigma_i^{\text{exp.}}$ the measured and $\sigma_i^{\text{theo.}}$ the predicted cross section of bin i, which depends on the free parameter $\alpha_s(M_Z)$ in the fit. The correlated systematic error for bin i associated with source k is denoted by Δ_{ik}. The systematic uncertainties are symmetric by definition. The ε_k are Gaussian random variables and may be interpreted as pulls, i.e. shifts caused by the systematics normalised to their uncertainty estimates. They are determined in the χ^2 fit, but are not counted as free parameters, because they are determined according to the Gaussian law hypothesis [11].

The experimental uncertainty of the free parameter in the fit, i.e. $\alpha_s(M_Z)$, is defined by that change in $\alpha_s(M_Z)$ which gives an increase in χ^2 of one unit with respect to the minimal value. The χ^2 minimisation, using MINUIT [12] for the combined fit, results in

$$\alpha_s(M_Z) = 0.1198 \pm 0.0019\ (\text{exp.}) \quad \text{with} \quad \chi^2/\text{ndf} = 27.4/29.$$

Several checks are performed to ascertain the stability of the fit due to the use of the Hessian method to estimate the experimental uncertainty. The contribution to the χ^2 in the simultaneous fit of each of the 30 data points and of each systematic source is determined. Most of the points are found to cluster around one unit of χ^2, so there is no strong tension in the simultaneous fit to both data sets from the different experiments. Another check performed quantifies the constraint provided by one data set to the other regarding the correlated systematic uncertainties. It is found that there is no significant change in the mean value of a given correlated source and only a small constraint is observed to be given by the data set of the other experiment when performing the simultaneous fit.

The sources of theoretical uncertainty considered include the renormalisation and factorisation scale and the uncertainties coming from the PDFs and the hadronisation models. The uncertainty on $\alpha_s(M_Z)$ coming from each source amounts to:

- the uncertainty coming from terms beyond NLO is estimated by varying the renormalisation scale by factors 0.5 and 2 in the calculations using the method of Jones et al. [13]: Instead of repeating the fit to the data with a different renormalisation scale used in the theory calculation, the following is performed. $\alpha_s(M_Z)$ is varied in the cross section calculation with the central μ_R until the cross section matches the result of the same calculation but with μ_R scaled by a factor 0.5 or 2 and the $\alpha_s(M_Z)$ taken from the fit to the data. This estimation is free from statistical fluctuations of the data as no new fit to the data is performed. The uncertainty on the value of $\alpha_s(M_Z)$ amounts to 0.0021;

- the effect of the uncertainty due to the value of the factorisation scale is estimated by varying μ_F by factors 0.5 and 2 in the calculations and repeating the fit to the data; it gives a contribution of 0.0010 to the uncertainty on $\alpha_s(M_Z)$;
- the uncertainty due to that of the PDFs is estimated by repeating the calculations using the 30 additional sets from the MRST2001 analysis, which take into account the statistical and correlated systematic experimental uncertainties of each data set used in the extraction of the PDFs. The resulting uncertainty on $\alpha_s(M_Z)$ is 0.0010;
- the uncertainty due to that on the hadronisation correction is estimated by using different Monte Carlo approaches to the parton-shower approximation to correct the NLO calculations for hadronisation effects: DJANGOH [14] using the Color Dipole Model as implemented in ARIADNE [15], and RAPGAP [16] using matrix elements matched with parton showers. The resulting uncertainty on $\alpha_s(M_Z)$ is 0.0004.

3 Result

The new HERA combined $\alpha_s(M_Z)$ value is

$$\alpha_s(M_Z) = 0.1198 \pm 0.0019\,(\mathrm{exp.}) \pm 0.0026\,(\mathrm{th.}) \quad \text{(HERA combined 2007)},$$

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 $\alpha_s(\mu_R = E_T)$ for several bins of E_T and integrated over Q^2 were performed. The results are shown in Fig. 2, compared to the pQCD evolution of $\alpha_s(M_Z)$ from 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. 3 together with the values obtained by each collaboration separately, the 2004 HERA average [2] and the 2006 world average [1]. 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.

A comparison to the most recent value of $\alpha_s(M_Z)$ from LEP [17], $\alpha_s(M_Z) = 0.1211 \pm 0.0010\,(\mathrm{exp.}) \pm 0.0018\,(\mathrm{th.})$, shows that the central values are compatible 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.

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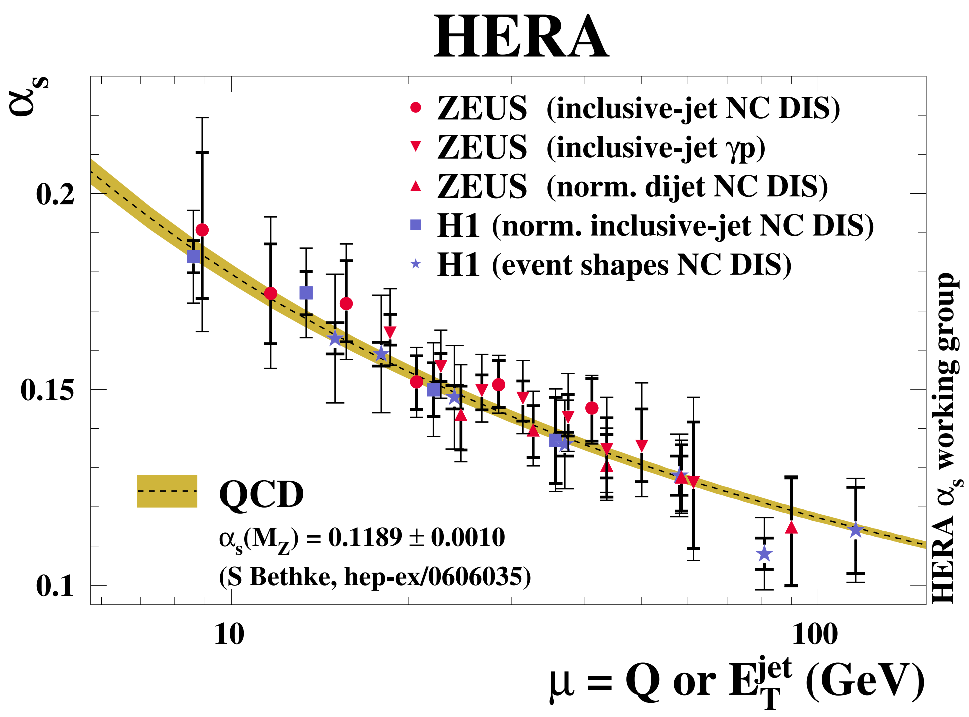

Figure 1: Determinations of $\alpha_s(\mu)$ from H1 and ZEUS shown with experimental errors (inner bars) and total errors (outer bars). The dashed line shows the two loop solution of the renormalisation group equation evolving the 2006 world average $\alpha_s(M_Z)$, with the band denoting the total uncertainty.

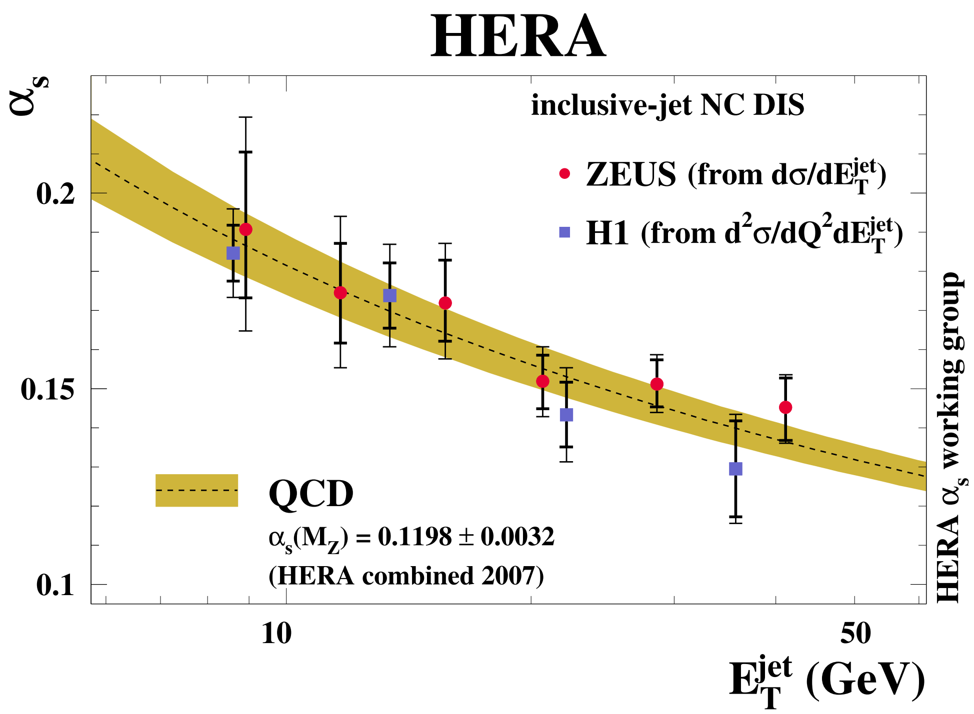

Figure 2: Results for the fitted values of $\alpha_s(E_T)$ using the inclusive jet cross sections from H1 and ZEUS. The inner (outer) error bar denotes the experimental (total) uncertainty for each fitted value. The dashed line shows the two loop solution of the renormalisation group equation evolving the HERA combined 2007 $\alpha_s(M_Z)$, with the band denoting the total uncertainty.

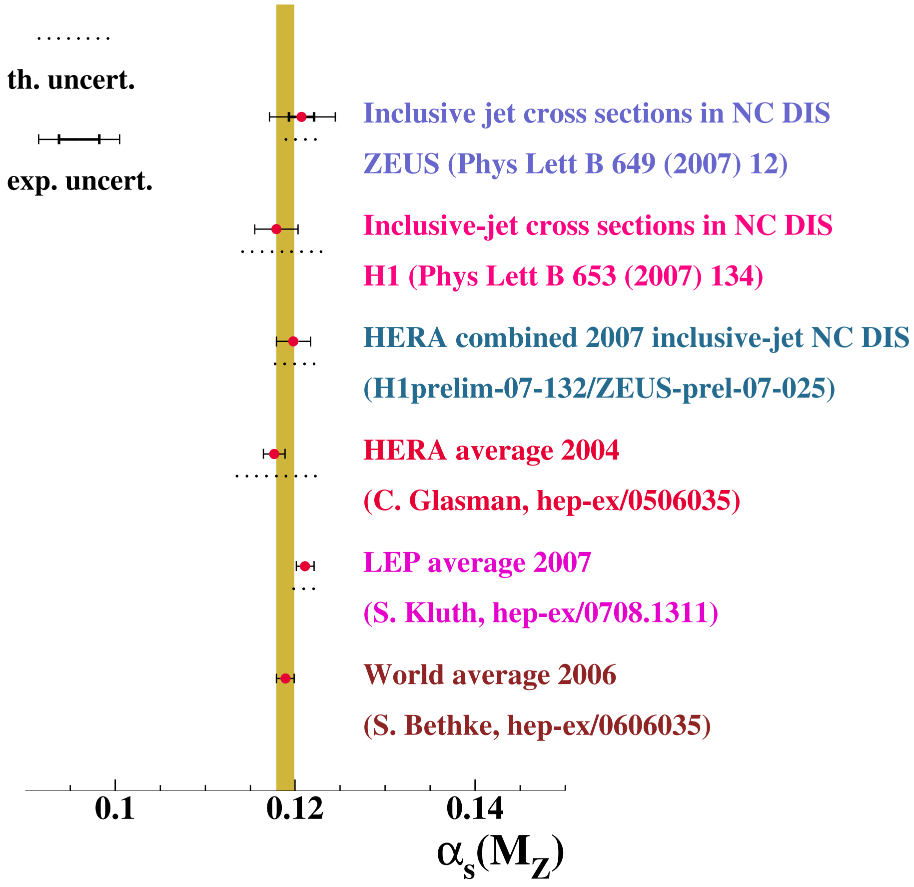

Figure 3: Determinations of $\alpha_s(M_Z)$ from ZEUS and H1 together with the HERA combined 2007 $\alpha_s(M_Z)$ value. For comparison, the HERA average 2004 and the world average 2006 are also shown. The shaded band represents the uncertainty of the world average.