THE GLUON DENSITY AND THE STRONG COUPLING FROM JETS IN DEEP-INELASTIC SCATTERING

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A QCD analysis of jet production in deep-inelastic scattering by H1 is presented. Fits are performed in which $\alpha_s(M_Z)$ and the gluon density in the proton are determined simultaneously and, with additional assumptions, separately. The strong coupling parameter is found to be $\alpha_s(M_Z) = 0.1186 \pm 0.0059$. The gluon density is determined at fairly large values of $10^{-2} < x < 10^{-1}$. An outlook is given on how the results might be improved in the future.

Hard jet cross sections in lepton-proton scattering can be written as a power series in the strong coupling α_s and a convolution of coefficient functions, calculable in perturbative QCD, and gluon and quark/anti-quark parton density functions (pdfs), which for example can be determined from measurements of the totally inclusive cross section in deep-inelastic scattering (DIS) and the evolution equations of QCD:

$$\begin{aligned}\sigma_{jet} = \sum_n \alpha_s^n(\mu_R) \int_0^1 dx \, \{ \; & c_{g,n}(\tfrac{x_{Bj}}{x}, \mu_R, \mu_F)\, g(x, \mu_F) \\ & + \sum_f c_{f,n}(\tfrac{x_{Bj}}{x}, \mu_R, \mu_F)\, q(x, \mu_F)\} \end{aligned} \tag{1}$$

Currently, inclusive jet and dijet cross sections have been calculated up to order α_s^2 . In this H1 analysis the renormalization scale is set to $\mu_R = E_{T,\mathrm{jet,\,Breit}}$ and the factorization scale to $\mu_F = \overline{E}_{T,\mathrm{jet,\,Breit}} = \sqrt{200}\,\mathrm{GeV}$ as will be explained later.

1 Analysis strategies

At least for the phase space of this analysis, accessible with current statistics of HERA I, jet cross sections are dominated by the gluon contribution, for which Eq. 1 indicates a strong correlation with α_s . H1 has therefore pursued the following analysis strategies. First α_s and the pdfs are fitted simultaneously, making use of jet and inclusive DIS cross sections. All pdfs cannot be fit individually, but Eq. 1 can be written in terms of three independent linear combinations of parton densities [2]. Due to the correlation between α_s and the gluon density, the value of $\alpha_s(M_Z)$ obtained is not very precise, but it is found to be consistent with the world average. Next, the more precise world average value of $\alpha_s(M_Z)$ is taken as input, and a fit of the gluon and quark densities, using the same data as before, is made. This leads to a "direct" determination of the gluon density from jet data. The third strategy followed is to take the pdfs from global fits and use the jet data alone to fit α_s .

2 Jet measurements

In order to make precise comparisons of the jet measurements with perturbative QCD calculations the following requirements have to be fulfilled:

- Usage of a factorizable jet algorithm, applied in the Breit frame, in order to guarantee the universal factorizability of initial state divergences also for jet cross sections.
- A jet definition which is infrared and collinear safe.
- Smallest hadronization corrections to the jet cross sections.

All three demands are fulfilled best by the inclusive $k_\perp$ algorithm [1]. The requirements of small hadronization corrections and of not too large $k = \sigma_{\rm NLO}/\sigma_{\rm LO}$ factors are met by restricting the data to photon virtualities $Q^2 > 150$ GeV^2 . Additionally, restricting the data to $Q^2 < 5000$ GeV^2 allows to neglect the weak neutral current processes in the QCD calculation and furthermore it ensures a small factorization scale dependence. Therefore, a fixed factorization scale of $\sqrt{200}$ GeV , i.e. the average transverse energy of the jets in the Breit frame, is chosen. As an important consequence, the chosen linear combination of parton densities are independent, since no evolution between different factorization scales takes place [2].

The kinematic region of the events is defined by the cuts on Q^2 mentioned above and on the inelasticity $0.2 < y < 0.6$. The jet phase space is defined by requiring $E_{T,\,\rm jet,\,Breit} > 7\,$GeV for the inclusive jet cross section and $E_{T,\,\rm jet1,2,\,Breit} > 5\,$GeV and $E_{T,\,\rm jet1,\,Breit} + E_{T,\,\rm jet2,\,Breit} > 17\,$GeV for the dijet cross section. In both cases the jets found in the Breit frame are boosted back to the laboratory frame and have to lie within the detector acceptance defined by the cut on pseudorapidity $-1 < \eta_{\rm jet,lab} < 2.5$.

The inclusive double differential jet cross section, measured as a function of Q^2 and $E_{T,\,\rm jet,\,Breit}$, can be found in [2]. Here the ratio of data to theory is shown as a function of the transverse jet energy in 4 bins of Q^2. For the NLO calculation the program DISENT by Catani and Seymour [3] was used with the parton density parameterization CTEQ5M1 [4] with $\alpha_s(M_Z) = 0.118$. The

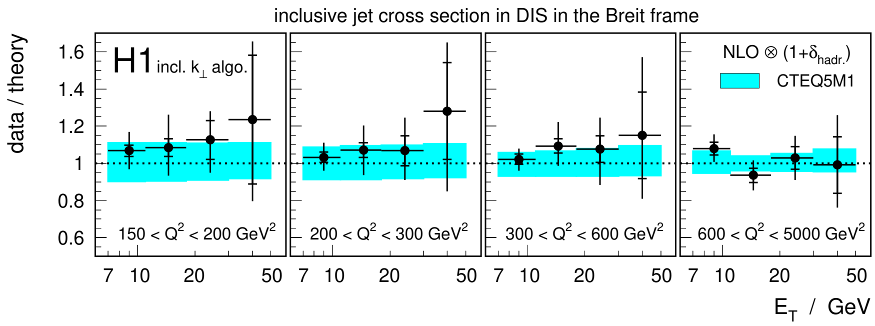

Figure 1. The ratio of the measured inclusive jet cross section and the NLO QCD prediction. The uncertainty of the theory is indicated by the band (the contributions from the renormalization and factorization scale dependence and the the hadronization corrections are added in quadrature.

data are found to be well described by NLO QCD over the whole range in Q^2 and $E_{T,\mathrm{jet,\,Breit}}$.

Similarly well described are the double differential dijet cross sections [2], measured in 4 bins in Q^2 as a function of $\overline{E}_{T,\mathrm{jet,Breit}}$ and of the parton momentum fraction $\xi = x_{Bj}\,(1 + M_{jj}^2/Q^2)$, which in LO is directly sensitive to the parton density at $x = \xi$.

3 Results

The strong correlation of $\alpha_s(M_Z)$ and the gluon density, obtained from fitting both to the inclusive DIS, the inclusive jet and the dijet cross section, can be seen in Fig. 2. While there is clearly good sensitivity to the product of $\alpha_s(M_Z)$ and the gluon density, each of them individually is currently not measured precisely. The results of global fits are also shown in Fig. 2.

Since the results are consistent with global fits, H1 has then used $\alpha_s(M_Z) = 0.1184 \pm 0.0031$, the much more precise world average, and fitted the gluon density and a linear combination of the quark densities. The data used in the fit were the inclusive DIS cross sections, which are directly sensitive to the quarks only, and the jet cross sections, which are in addition directly sensitive to the gluon. The result for the gluon density is shown in Fig. 3, including a one standard deviation error band, together with the results of global fits for which no error bands are available.

Having found gluon (and quark) densities consistent with those from

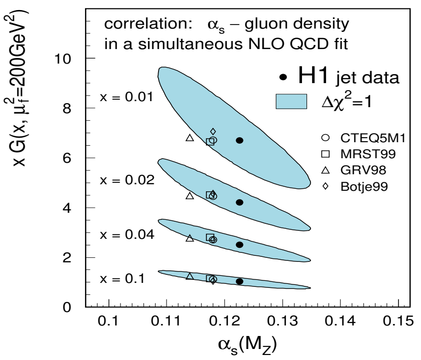

Figure 2. The correlation of the fit results for $\alpha_s(M_Z)$ and the gluon density. The central fit result is indicated by the full marker. The error ellipses include the experimental and theoretical uncertainties.

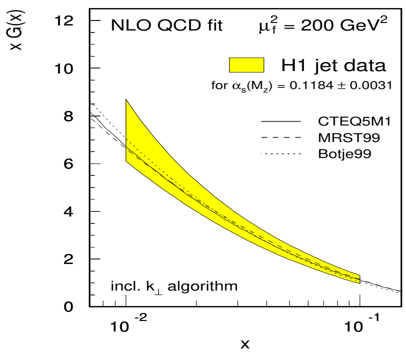

Figure 3. The gluon density in the proton from the QCD fit, assuming for $\alpha_s(M_Z)$ the world average value. The error band includes the experimental and theoretical uncertainties as well as the uncertainty of $\alpha_s(M_Z)$.

global fits, one of the parton densities (CTEQ5M1) from global fits is taken, and α_s is fitted to the inclusive jet cross section $d^2\sigma_{jet}/dE_T dQ^2$. The result is shown in Fig. 4. The data show the "running" of $\alpha_s(E_T)$ consistent with the renormalization group equation. The final result for the strong coupling is $\alpha_s(M_Z) = 0.1186 \pm 0.0030$ (exp.) $^{+0.0039}_{-0.0045}$ (th.) $^{+0.0033}_{-0.0023}$ (pdf). The experimental error consists of a small stat. error of 0.0007 and of syst. errors of which the largest is the one due to the hadronic calorimeter energy scale uncertainty of $\pm 4\%$. The theory error consists of the hadronization uncertainty (≈ 0.0030) and the renormalization scale uncertainty (≈ 0.0030), the latter is obtained by varying the scale up and down by a factor of 2. Finally, the error due to the pdfs was obtained by using the uncertainties of the pdfs determined recently by Botje [5]. They include the stat. and syst. errors of the DIS data used in the fit and the syst. errors due to different fit assumptions. The largest single contribution is due to the factorization scale dependence. The uncertainty in $\alpha_s(M_Z)$, obtained this way, is slightly larger than what one finds from the spread in $\alpha_s(M_Z)$ using different global pdfs in the fit [2].

4 Outlook

Consistent new determinations of $\alpha_s(M_Z)$ and of the gluon density from jet data and from inclusive DIS measurements have been obtained from HERA

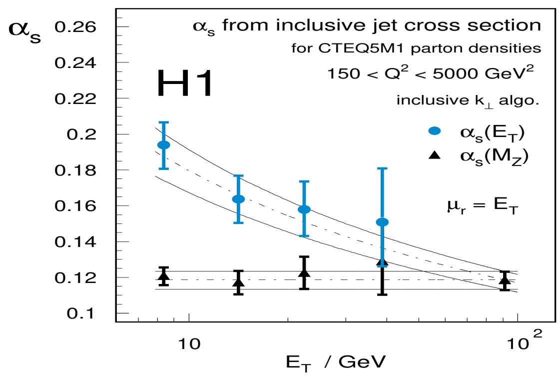

Figure 4. Determination of α_s from the inclusive jet cross section for the renormalization scale $\mu_R = E_T$. The results are shown for each value of E_T (circles) including experimental and theoretical uncertainties. The single values are extrapolated to the Z^0-mass (triangles). The final result for $\alpha_s(M_Z)$ (rightmost triangle) is obtained in a combined fit.The lower curves represent the combined fit result and its uncertainties. The upper curves show the predictions of the renormalization group equation.

with remarkably small errors, which allow to have an impact on the world average. Can we hope to reduce them further?

Experimentally, the largest error source is the hadronic energy scale uncertainty, which is currently $\pm 4\%$, but which is expected to be reduced to $\pm 2\%$ in the near future. Some improvements can be expected by optimization of the analyses with respect to error reduction, for example the minimum jet E_T requirement. By using the ratio $\sigma_{dijet}/\sigma_{DIS}$, ZEUS [6] has shown that, at very high Q^2, the uncertainty in $\alpha_s(M_Z)$ due to the pdfs can be significantly reduced because of partial cancellations. This may be even more so the case for the ratio $\sigma_{3-jet}/\sigma_{2-jet}$, which has recently been measured by H1 [7]. By making the same cut on the invariant mass of the 2-jet and the 3-jet system the pdfs are probed at the same value of x, thereby substantially reducing the sensitivity to the gluon density [7]. Finally, high statistics will provide access to very high jet E_T, which are sensitive to the convolution of α_s and the quark densities, reducing the strong correlation between $\alpha_s(M_Z)$ and the gluon density. If better theory and a better understanding of hadronization corrections allow to use data at lower Q^2, we could significantly increase the jet statistics and have the advantage of a longer lever arm in determining $\alpha_s(M_Z)$.

On the theoretical side, the largest error sources are the renormalization scale and the hadronization uncertainty. NNLO QCD calculations will reduce the scale dependence of the jet cross sections and also of the pdfs. Resummed calculations matched to NLO for low Q^2, where $E_T^2 >> Q^2$, would allow to use the low Q^2 jet data with the advantages mentioned above. Finally, a Monte Carlo generator, including NLO matrix elements matched to parton showers and including hadronization, may allow better estimates of the hadronization corrections.

5 Summary

Inclusive jet and dijet cross sections for $150 < Q^2 < 5000$ GeV^2 and for $7 < E_T < 50$ GeV are well described by NLO QCD. QCD fits for $\alpha_s(M_Z)$ and the gluon density show strong anti-correlations. Taking the world average value for $\alpha_s(M_Z)$ the gluon density was fitted in the range $0.01 < x < 0.1$ and is found to be in good agreement with results from global analyses of parton densities. Using the latter parton densities and fitting $\alpha_s(M_Z)$ to the inclusive jet cross sections yields $\alpha_s(M_Z) = 0.1186 \pm 0.0059$ (tot.), in good agreement with the world average and competitive with other measurements.

With the luminosity upgrade of HERA II *and* progress in theory and experiment, we can expect to further decrease the uncertainty on $\alpha_s(M_Z)$ and the gluon density.

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