Determination of the Strong Coupling Constant in Jet Production at HERA
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Abstract
Recent \( \alpha_s \) determinations from jet production at HERA are presented. Three different observables lead to consistent \( \alpha_s \) values. The most accurate result is:

\[
\alpha_s(M_Z) = 0.1181 \pm 0.0030 \text{(exp.)} \pm 0.0039 \text{(theo.)}^{+0.0036}_{-0.0046} \text{(pdf)}
\]

1. Introduction
Perturbative Quantum Chromodynamics (pQCD), the theory describing short distance strong interactions, has a single free parameter, the strong coupling constant \( \alpha_s \). This coupling depends on the renormalisation scheme and the energy scale. At the reference scale, which is customarily chosen as the mass of the \( Z^0 \) boson, the strong coupling is presently known to an accuracy of about 4% [1]. This is more than a factor of 10 less precise than the coupling of the weak force. Measurements of \( \alpha_s \) over a wide energy range provide a fundamental test of the evolution predicted by the QCD \( \beta \)-function and can severely constrain physics beyond the Standard Model.

Precise determinations of \( \alpha_s \) have been performed in \( e^+e^- \) annihilation processes over a large range of centre of mass energies from 14 < \( \sqrt{s} \) < 189 GeV using jet rates, event shapes, \( \tau \) decays and the inclusive ratio of hadron to lepton branchings [2].

Jet production at hadron colliders is a particularly well suited process to measure the energy dependence of \( \alpha_s \) in one single experiment. However, the presence of hadrons in the initial state leads to the complication that the measured cross section always depends on the product of \( \alpha_s \) and the parton density functions (PDF).

The high centre of mass energy (s) of HERA, colliding 27.5 GeV positrons on 820 GeV protons, allows hard processes to be studied in deep-inelastic scattering (DIS). Particularly well suited for pQCD studies is the Breit frame in which the photon is purely space-like and collides head-on with the proton. Besides the photon virtuality, \( Q^2 \), the transverse energy \( E_T \) produced in the Breit frame provides a hard scale.

Jet cross sections at high \( E_T \) are collinear and infrared safe observables which can be calculated in pQCD.

Figure 1. Examples of \( \mathcal{O}(\alpha_s) \) and \( \mathcal{O}(\alpha_s^2) \) Feynman diagrams dijet events in \( e^+e^- \) collisions.

The jet cross section \( \sigma_{jet} \) can be expanded to:

\[
\sum_{a,n} \alpha^a_s(\mu_R^2) \int_0^1 d\xi C_{a,n}(x_{Bj}/\xi, \mu_T^2, \mu_T^2, \ldots) f_{a/p}(\xi, \mu_T^2),
\]

where \( x_{Bj} = Q^2/(2p \cdot \gamma) \), \( \xi = x_{Bj} (1 + M^2_{j,j}/Q^2) \) is in leading order (LO) the fractional momentum of the struck parton in the proton and \( M_{j,j} \) the invariant dijet mass. \( \mu_T \) is the renormalisation (factorisation) scale. The perturbatively calculable coefficients \( C_{a,n} \) are presently known to next-to-leading order (NLO). The jet cross section is directly sensitive to \( \alpha_s \) and the gluon (\( f_{q/p} \)) and quark (\( f_{q/p} \)) densities in the proton. For low \( Q^2 \) (below \( \approx 40 \text{ GeV}^2 \)) jet cross sections calculated in NLO strongly depend on \( \mu_T \)[3,4]. pQCD analyses are therefore better performed at high \( Q^2 \), where also hadronisation effects are smaller [5].

Double differential inclusive dijet cross sections \( d^2\sigma/dx\,dQ^2 \) and \( d^2\sigma/dy\,dQ^2 \) for \( 200 < Q^2 < 5000 \text{ GeV}^2 \), where jets are defined by the inclusive \( K_T \) algorithm [6] asking for \( E_T > 5 \text{ GeV} \), \( E_{T,1} + E_{T,2} > 17 \text{ GeV} \) and \( -1 < \eta_{ab} < 2.5 \) have been used for a preliminary extraction of the gluon density in the range 0.01 \( \leq \xi \leq 0.1 \) at fixed \( \mu_T^2 = 200 \text{ GeV}^2 \)[6]. In this analysis \( \alpha_s \) has been set to

\[\hat{\eta} = \ln \tan \theta/2.\]
the world average. $F_2$ data \cite{3} for $200 < Q^2 < 650$ GeV$^2$ have been included in a combined fit to get an additional constraint on the quark densities.

At this conference new preliminary results have been presented where the opposite strategy has been pursued. The parton densities have been taken from global fits to inclusive DIS data and exclusive high-$E_T$ processes and then $\alpha_s$ is fitted. Either sets of PDF with different input $\alpha_s$ have been used to account for the anti-correlation between $\alpha_s$ and the PDF or the dependence on the PDF is included in the systematic error. The final aim is to perform a consistent simultaneous fit of both $\alpha_s$ and the PDF.

2. $\alpha_s$ from Inclusive Jet Cross Sections

The single inclusive jet cross section $d\sigma/dQ^2 dE_T$ has been measured in four different $Q^2$ regions within $150 < Q^2 < 5000$ GeV$^2$ and $0.2 < y = Q^2/(s x_{Bj}) < 0.6$ by the H1 collaboration. Jets are defined by the inclusive $K_T$ algorithm requiring $E_T > 5$ GeV in the range $-1 < \eta_{lab} < 2.5$. The data are corrected for detector effects. Over the whole phase space reaching $E_T$ up to 50 GeV a NLO calculation based on DISENT \cite{4} using the CTEQ5M \cite{8} PDF with $\mu_r^2 = E_T^2$ and $\mu_f^2 = 200$ GeV$^2$ describes the data. Hadronisation effects lower the NLO prediction by about 3–10\% \cite{3}. For each $E_T$ and $Q^2$ bin $\alpha_s$ is adjusted to the measured cross section using a $\chi^2$ minimisation where the systematic errors are included in the fit \cite{3}. All results are consistent with each other. In Fig. 4 the results are shown as a function of $E_T$ after having combined the four $Q^2$ bins. The fitted $\alpha_s$ evolve as predicted by the renormalisation group equation. The combined $\alpha_s(M_Z^2)$ result is:

$$0.1181 \pm 0.0030 \ (\text{exp.})^{+0.0039 \ (\text{theo.})}_{-0.0015 \ (\text{pdf.})}$$

The largest contribution to the experimental error comes from the uncertainty on the hadronic energy scale. The theoretical error is mainly determined by the uncertainty of the hadronisation corrections and by the $\mu_r$ dependence. The contribution obtained by varying $\mu_r^2$ by a factor of 4 amounts to $-0.0034$. The hadronisation uncertainties are estimated in a very conservative way using the QCD Monte Carlo models. Since the spread between this models is rather small, half of the size of the hadronisation corrections, but at least 3\%, is assigned as systematic uncertainty. If $\mu_r^2 = Q^2$ instead of $\mu_r^2 = E_T^2$ is used a consistent $\alpha_s(M_Z^2)$ result is obtained:

$$0.1221 \pm 0.0034 \ (\text{exp.})^{+0.0054 \ (\text{theo.})}_{-0.0016 \ (\text{pdf.})}$$

For $\mu_r^2 = Q^2$ the $\mu_r$ dependence increases by \approx 40\%.

The systematic uncertainty on the PDF is difficult to estimate, because none of the global analyses has yet provided PDF errors. Since the fit results of the different groups, MRST \cite{10}, and CTEQ \cite{8}, are based on similar data sets and assumptions, the spread of different parametrisation does not give a realistic error evaluation. Recently the CTEQ collaboration \cite{11} has investigated possible variations on the gluon distribution using different parametrisations and allowing the quality of the fit to be degraded. The resulting parametrisation is the first step towards the estimation of uncertainties, but can not replace a proper error analysis.

Another point of concern is the influence of the $\alpha_s$ value used when deriving the PDF. If a strong correlation between the fit result and the initial assumption on $\alpha_s$ was found, it would be questionable whether the ansatz to fix the PDF and to extract $\alpha_s$ would be meaningful. This dependence can be tested by means of series of parton distributions scanning from low to high values of $\alpha_s$.

A comprehensive study of the fitted $\alpha_s$ on all available recent PDF, is presented in Fig. 3. The largest deviation to the central result obtained with the CTEQ5M parametrisation is quoted as

![Figure 2. $\alpha_s$ fit result versus the jet $E_T$. The lines indicate the prediction of the renormalisation group equation for the combined results and their uncertainty.](image-url)
systematic error. Only for the highest $E_T$ a slight dependence on the $\alpha_s(M_Z^2)$ value used in the global fits is found. For all other bins no correlation is observed. This is different from the observation made by the CDF collaboration \[12\] in an analysis of single inclusive jet cross sections measured in $p\bar{p}$ collisions where a strong correlation between the $\alpha_s$ used in the PDF and the fit result was found.

3. $\alpha_s$ from Dijet Rates

The ZEUS collaboration has measured dijet cross sections and rates in the phase space $470 < Q^2 < 20000$ GeV$^2$ and $0 < y < 1$. Jets are defined as in the dijet analysis described before, except that the two highest $E_T$ (and not all) jets have to fulfill $-1 < \eta_{lab} < 2$. In addition, only events with exactly two jets are considered. The exclusive dijet cross sections as a function of $E_T$, $M_{jj}$, $\eta_{lab}$, $x_{Bj}$, $z_{p,1} = E_1(1 - \cos \theta_1)/(\sum_{k=1,2} E_k(1 - \cos \theta_k))$, and $\xi$ are - both in shape and in absolute magnitude - well described by a NLO calculation using CTEQ4M \[13\] for $\mu_r^2 = \mu_f^2 = Q^2$. The data are corrected for detector, electroweak radiation and hadronisation effects. Hadronisations corrections are at most 10% and decrease with increasing $Q^2$. For $Q^2 > 5000$ GeV$^2$ the contributions from $Z^0$ exchange become visible. They have been subtracted from the data.

The good description of the data allows an extraction of $\alpha_s$ from $R_{2+1}(Q^2) = \sigma_{2+1}(Q^2)/\sigma_{tot}(Q^2)$.

The dijet rates shown in Fig. 4 are compared to NLO QCD calculations based on the CTEQ4A PDF series which have been fitted for different $\alpha_s$ assumptions. This series is also used to parametrise the anti-correlation between $\alpha_s$ and the PDF \[14\]. The value of $\alpha_s$ is obtained from a $\chi^2$ minimisation: $0.120 \pm 0.003$ (stat.) $+0.005$ (exp.) $-0.003$ (theo.)

The experimental systematic error is dominated by the uncertainty on the hadronic energy scale ($\pm 0.005$). QCD Model dependencies to unfold the data to parton level account for an error of $\pm 0.001$. The theoretical uncertainty is estimated by varying the renormalisation scale $\mu_r^2 = Q^2$ by a factor of 2 ($\pm 0.002$), by replacing the assumed PDF by MRST sets ($-0.002$) and by taking DISASTER++ \[15\] instead of DISENT ($\pm 0.002$). If $\mu_r^2$ is varied by a factor of 4 as in the previous analysis, the $\mu_r$ uncertainty increases to $\pm 0.004$. The dijet rates change only by at most 2.5% when the PDF from the CTEQ gluon uncertainty study is used. The influence on the $\alpha_s$ result is therefore expected to be small.

4. $\alpha_s$ from Differential Jet Rates

H1 has measured $1/N_{tot}(dn/dQ^2dy_2)$ for $Q^2 > 150$ GeV$^2$ and $0.1 < y < 0.7$. All particles are clustered on the basis of a distance measure $y = d_{i,j}/\text{scale}$, where $d_{i,j} = 2 \min(E_i^2, E_j^2)/(1 - \cos \theta_{i,j})$, until 2 + 1 jets are found. $y_2$ is the smallest value $\dagger$ +1 denotes the proton remnant. $E_i$ is the energy of the particles and $\theta_{i,j}$ the angle between them.
of $y$ where two jets can be resolved. It is therefore a measure for the jet structure. Two jet algorithms are used. In both cases the data are described by a NLO calculation based on CTEQ5M [17].

The $K_T$ jet algorithm for DIS [16] is applied in the Breit frame and scale is set to 100 GeV$^2$. The proton remnant $p$ is included as particle with $d_k = 2E_T^2(1 - \cos \theta_i)$. After a cut $y_2 > 0.8$ only events with $E_T > 10$ GeV in the Breit frame remain. A $\chi^2$ minimisation gives $\alpha_s(M_Z^2)$:

$$0.1143^{+0.0075}_{-0.0089} \; (\text{exp.}) \; ^{+0.0074}_{-0.0064} \; (\text{theo.}) \; ^{+0.0008}_{-0.0054} \; (\text{pdf})$$

A variant of the JADE algorithm is applied in the HERA laboratory frame and the squared invariant mass of the hadronic final state $W^2$ is used as scale, applied in the HERA laboratory (“mod. Durham algorithm”). A massless particle is added in the clustering procedure to account for the escaped longitudinal momentum. $y_2$ is required to be above 0.005 to select hard processes. The fit result is:

$$0.1189^{+0.0064}_{-0.0081} \; (\text{exp.}) \; ^{+0.0059}_{-0.0046} \; (\text{theo.}) \; ^{+0.0013}_{-0.0055} \; (\text{pdf})$$

The quoted values are obtained for $Q^2 > 575$ GeV$^2$, the lower $Q^2$ regions give consistent results. The experimental errors are dominated by the energy scale uncertainty and by the QCD model dependence of the detector correction. The theoretical uncertainty is given by the hadronisation correction ($\pm 0.0026$) and the $\mu_r$ dependence: $^{+0.0062}_{-0.0036}$ for $\mu_r^2 = Q^2$ and $^{+0.0025}_{-0.0020}$ for $\mu_r^2 = E_T^2$. The correlation between the fitted $\alpha_s$ and the value assumed in the PDF seems to be - in particular at low $Q^2$ - stronger for jet rates than for jet cross sections.

5. Summary

$\alpha_s(M_Z^2)$ has been determined in NLO from jet observables in DIS at HERA (see Fig. 5). The result is consistent with the world average and has an error of about 0.006. This is quite a remarkable result, since it is only slightly less precise than the world average value having an error of 0.004 [4].

In future, fitting technique using $F_2$ and jet data should be further developed to allow a simultaneous fit of $\alpha_s$ and the PDF from HERA data alone.

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References

[1] S. Bethke, In IV$^{th}$ Int. Symp. on Rad. Corrections (1998), Barcelona (Spain) hep-ph/9812026.
[2] T. Carl, hep-ph/9906541.
[3] M. Wobisch and T. Wengler, hep-ph/9907280.
[4] S. D. Ellis and D. E. Soper, Phys. Rev. D 48 (1993) 3160.
[5] H1 Collab., In XXIX Int. Conf. on HEP (1998), paper: 520, Vancouver (Canada), M. Wobisch, hep-ph/9811210.
[6] H1 Collab., In XXIX Int. Conf. on HEP (1998), paper: 533, Vancouver (Canada).
[7] S. Catani and M.H. Seymour, Nucl. Phys. B 485 (1997) 291,Erratum–ibid. B 510 (1997) 503.
[8] CTEQ Collab., hep-ph/9903282.
[9] M. Wobisch, Thesis, in preparation (1999), University Aachen (Germany).
[10] A.D. Martin et al., Eur. Phys. J C 4 (1998).
[11] J. Huston et al., Phys. Rev. D 58 (1998) 114034.
[12] V.D. Elvira, In XXXIII Rencontres de Moriond (1998), Les Arc (France).
[13] CTEQ Collab., Phys. Rev. D 55 (1997)1280.
[14] E. Tassi, Thesis, in preparation (1999), University Hamburg (Germany).
[15] D. Graudenz, hep-ph/9710244v2.
[16] S. Catani, Yu.L. Dokshitzer and B.R. Webber, Phys. Lett. 285 (1992) 291.
[17] N. Tobien, Thesis, in preparation (1999), University Hamburg (Germany).