DETERMINATION OF THE STRONG COUPLING CONSTANT USING THE INCLUSIVE JET CROSS SECTION IN $p\bar{p}$ COLLISIONS at $\sqrt{s} = 1.96$ TeV

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This talk presents a determination of the strong coupling constant α_s using a measurement of the inclusive jet cross section in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV by the DØ Experiment. The energy dependence of the strong coupling constant is determined using jet measurements in the transverse momentum range $50 < p_T < 145\,\mathrm{GeV}/c$. Comparing data with perturbative QCD calculations to order $O(\alpha_s^3)$ plus threshold corrections at $O(\alpha_s^4)$, we obtain the result $\alpha_s(M_Z) = 0.1161^{+0.0041}_{-0.0048}$. This is the most precise result obtained at a hadron-hadron collider

1 Introduction

The theory of quantum chromodynamics (QCD) has proven successful at describing the phenomenology of strong interactions over enormous ranges of interaction energies, from scales slightly higher than the mass of the proton upwards to the most energetic collisions so far observed. Although the value of the strong coupling constant α_s is not predicted at any finite scale, its energy dependence is calculable to high accuracy using perturbative QCD. A dramatic consequence of this energy dependence is that the strong force between quarks and gluons weakens when it is probed at increasingly small distance scales, leading to asymptotic freedom. The renormalization group equation (RGE) describes the dependence of α_s on the renormalization scale μ_r, or equivalently, on the momentum transfer q^2 in a strong interaction. Therefore, the determination of $\alpha_s(\mu_r)$ over a large range of momentum transfer serves as a powerful test of the RGE and asymptotic freedom. A variety of processes have been used to determine α_s, including measures of hadronic jet production rates in ep and e^+e^- collisions, precise measures of the hadronic branching fraction in τ decays, and calculations on the lattice with constrains from data on quarkonia states [1]. A previous determination of a_s in hadron-hadron collisions, presented by the CDF Collaboration and based on the inclusive jet cross section in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV, reported the value $a_s(M_Z) = 0.1178^{+0.0081}_{-0.0095}(\mathrm{exp.})^{+0.0071}_{-0.0047}(\mathrm{scale}) \pm 0.0059(\mathrm{PDF})$ [2]. Taking advantage of improvements in experimental uncertainties, advances in perturbative QCD calculations, and progress in modeling of parton distributions, we present a new determination [3] of α_s and its q^2 dependence using data from the measurement of the inclusive jet cross section [4,5] with the DØ detector [6] in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron Collider.

The D0 measurement of the inclusive jet cross section $d^2\sigma_{jet}/dp_T d|y|$ is the most precise measure of differential jet production rates at a hadron collider. Jets are reconstructed using the Run II iterative cone algorithm [7] with cone radius of 0.7 in rapidity and azimuthal angle (y, ϕ). Data are corrected to the particle level [8] for jet transverse momenta from 50 GeV to $600\,\mathrm{GeV}/c$ in six regions of $|y|$. Uncertainties are smaller than those from parton distribution

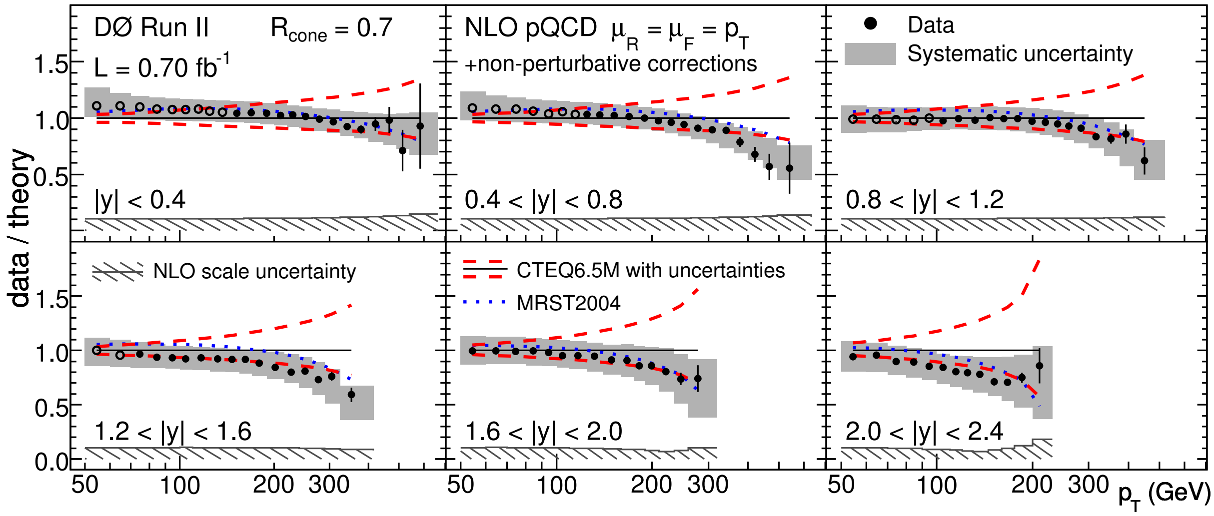

Figure 1: Data divided by theory for the D0 inclusive jet cross section as a function of jet p_T in six $|y|$ bins. Systematic uncertainties on data are shown by the shaded band. NLO pQCD calculations using the CTEQ6.5M PDFs and including non-perturbative corrections are compared to the data. The CTEQ6.5 PDF uncertainties are shown as long dashed lines and the predictions with MRST2004 PDFs as short dashed lines. The scale uncertainty at NLO is $\approx 10-15\%$. Open circles mark the points used in the determination of α_s.

functions (PDFs) and scale dependence in NLO pQCD over a wide kinematic range as illustrated in Fig. 1. These data probe momentum scales in common with ep data and also scales well beyond those accessible in $ep \to$ jets and other determinations of α_s.

2 Analysis Method

The calculation of the inclusive jet cross section in hadron collisions using pQCD depends on α_s, a series of perturbative coefficients c_n, and parton distribution functions with parametrizations also depending on α_s. Thus the cross section can be written as:

$$\sigma^{jet}_{pert}(\alpha_s) = \left(\sum_n \alpha_s^n c_n\right) \otimes f_1(\alpha_s, x_1) \otimes f_2(\alpha_s, x_2) \tag{1}$$

where the sum is over all powers n of α_s. $f_{1,2}$ denote PDFs for the initial state hadrons with convolution over the momentum fractions x_1, x_2 of the partons. The dependence of α_s and the PDFs on the momentum scale is implicit. Each point in the inclusive jet cross section is sensitive to $\alpha_s(p_T)$ and hence the running of α_s.

We use a combined fit of selected data points along with the RGE to determine the value of $\alpha_s(M_Z)$. The method is summarized in Eqn. 2:

$$\chi^2(\xi, \vec{\epsilon}, \vec{\alpha}) = \sum_{i=1}^{npoints} \frac{\left[d_i - t_i(\xi, \vec{\alpha})\left(1 + \sum_j \delta_{ij}(\epsilon_j)\right)\right]^2}{\sigma^2_{i,stat.} + \sigma^2_{i,uncorr.}} + \sum_j \epsilon_j^2 + \sum_k \alpha_k^2 \tag{2}$$

A χ^2 is minimized with respect to the fit parameter $\xi = \alpha_s(M_Z)$. The data are represented by d_i and t_i is the pQCD theory including non-perturbative corrections for hadronization and the underlying event. The theory term contains the matrix element and depends on the PDFs. The symbols $\sigma^{stat.}$ and $\sigma^{uncorr.}$ represent statistical uncertainties on the data and systematic uncertainties that are uncorrelated between individual points. Both the data and theory are allowed to vary according to their correlated systematic uncertainties, $\vec{\epsilon}$ and $\vec{\alpha}$, respectively, where these are constrained by prior knowledge of systematics (via the two terms on the right). The theory fitted to the data is calculated at $O(\alpha_s^3)$ next-to-leading order (NLO) with additional $O(\alpha_s^4)$ 2-loop terms from threshold resummation corrections [9], significantly reducing dependencies on renormalization and factorization (μ_f) scales in the calculation. The PDFs are parameterized at next-to-next-to-leading order (NNLO) using the distributions given by MSTW2008 [10,11]. This NNLO PDF set is determined for 21 different values of $\alpha_s(M_Z)$ in the range 0.107 - 0.127 in steps of 0.001, allowing for accurate interpolation to arbitrary values of $\alpha_s(M_Z)$ within the range provided. The calculations are performed using the program fastNLO [12]. Combining pQCD calculations from NLOJET++ [13,14] and corrections from Ref. [9], fastNLO allows fast recalculations of jet cross sections for arbitrary PDFs. Calculations are performed using $\mu_f = \mu_r = p_T^{\text{jet}}$ and uncertainties from scale dependence in the theory are estimated by varying the scales by factors 0.5 and 2.0.

The MSTW2008 PDFs include the D0 inclusive jet data and these data provide dominant constraints on the parameterization of the momentum fractions carried by gluons at large-x. In the absence of having full documentation of the correlations between experimental and PDF uncertainties, the analysis is restricted to kinematic regions where the Tevatron jet data do not provide significant constraints to the PDFs. This corresponds to gluon momentum fractions $\lesssim 0.3$. At leading order the parton x values may be determined in di-jet events via $x_1 = x_T(e^{y_1} + e^{y_2})/2$ and $x_2 = x_T(e^{y_1} - e^{y_2})/2$ with $x_T = 2p_T/\sqrt{s}$. Because the inclusive jet cross section is binned according to the p_T of the leading jet only, it is not possible to define a unique mapping for a given bin in p_T and $|y|$. An approximation is based on the variable $\tilde{x} = x_T \cdot (e^{|y|} + 1)/2$ that represents the maximum of the values x_1, x_2 if all sub-leading jets in the event are treated as single jet with rapidity $|y| = 0$. Requiring $\tilde{x} < 0.15$ restricts the data points to those where a majority of events satisfy $x_{max} < 0.25$. This leaves 22 of 110 data points to use in the measurement of α_s, these points are shown as open circles in Fig. 1. Since this requirement is somewhat arbitrary, variations in the cut value are used to determine an additional systematic uncertainty on the measurement.

3 Results

Data with similar p_T from different $|y|$ intervals are grouped into nine transverse momentum intervals to determine $\alpha_s(M_Z)$ and $\alpha_s(p_T)$. A combined fit to the data points and inclusion of all systematic uncertainties yields $\alpha_s(M_Z) = 0.1161^{+0.0041}_{-0.0048}$. The results for the combined p_T values in the range of $50 < p_T < 145\,\text{GeV}/c$ are given in Fig. 2(a). The full uncertainties shown for each value are largely correlated among the data points. Figure 2(b) displays the same data plotted as a function of $1/log(p_T)$, showing consistency with asymptotic freedom. The largest contribution to the uncertainties is due to the correlated experimental uncertainty, dominated by jet energy calibration, jet transverse momentum resolution, and normalization by the integrated luminosity. Scaling the non-perturbative corrections by factors of 0.5 and 2.0 changes the central result by $^{+0.0003}_{-0.0010}$. Replacing the MSTW2008 NNLO PDFs by the CTEQ 6.6 PDFs leads to an increase of 0.5%, this is significantly less than the PDF uncertainty of $^{+0.0012}_{-0.0011}$. Removing the 2-loop threshold corrections and using NLO pQCD together with the MSTW2008 NLO PDFs and the 2-loop solution to the RGE yields $\alpha_s(M_Z) = 0.1201^{+0.0072}_{-0.0059}$. This increase in the central value, originating from the missing $O(\alpha_s^4)$ contributions, is well within the scale uncertainty of the NLO result.

The results obtained for $\alpha_s(p_T)$ are consistent with the energy dependence predicted by the RGE and extend the results based on the HERA jet data [15]. The value obtained for $\alpha_s(M_Z)$ is consistent with the the world average value [1] and are of similar precision to those obtained in $ep \rightarrow$ jets. This is the most precise measure of the strong coupling constant at a hadron collider and provides the highest momentum scale test of the running of α_s.

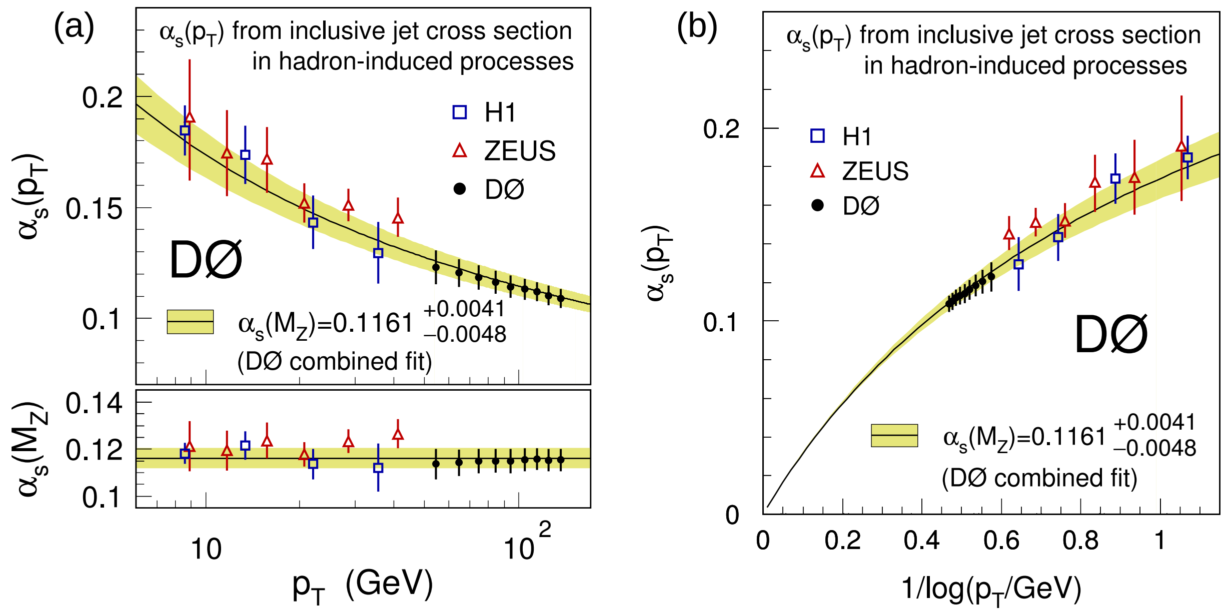

Figure 2: (a) Measurement of $\alpha_s(p_T)$ (top) and $\alpha_s(M_Z)$ (bottom). Data points are shown with their total uncertainties. (b) The same plotted as a function of $1/log(p_T)$ showing consistency with asymptotic freedom.

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