

Determination of the strong coupling constant from inclusive jet cross section in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV with the DØ experiment

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The strong coupling constant α_s and its dependence on the momentum scale is determined from the p_T dependence of the inclusive jet cross section in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV measured with the DØ experiment. The jet transverse momentum range of $50 < p_T < 145$ GeV contributes to the determination. Using perturbative QCD calculations to order $\mathcal{O}(\alpha_s^3)$ combined with resummed threshold corrections to order $\mathcal{O}(\alpha_s^4)$ an $\alpha_s(M_Z) = 0.1161_{-0.0048}^{+0.0041}$ is obtained. This is the most precise result from a hadron-hadron collider.

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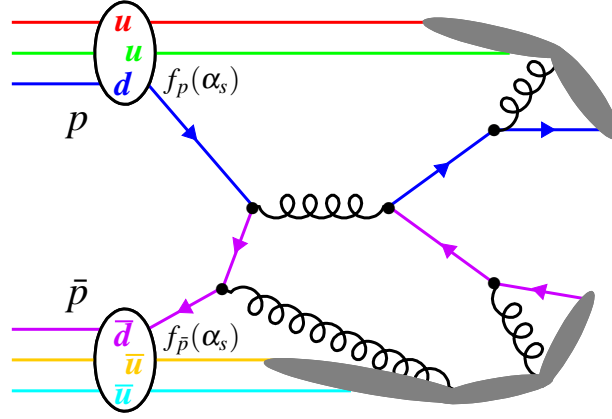


Figure 1: A drawing, illustrating jet production in a proton anti-proton collision with the hard scattering process, initial state, final state radiation and hadronisation (jet fragmentation) including the underlying event.

1. Introduction

A remarkable property of quantum chromodynamics (QCD) is the property of asymptotic freedom. It is reflected by the prediction of the renormalisation group equation (RGE) dependence of the strong coupling constant α_s on the momentum scale. Experimental tests of asymptotic freedom require precise determinations of α_s over a large range of momentum scales. Its determination discussed here [1][2] is based on an inclusive jet cross section measurement [3] with the $D\emptyset$ detector [4]. The inclusive jet cross section $d^2\sigma_{\text{jet}}/dp_T d|y|$ has been measured using the Run II iterative midpoint cone ($R = 0.7$) algorithm [5] in the energy scheme. 110 data points are measured as a function of the momentum transverse to the beam axis, p_T in six equidistant regions of $|y|$ (absolute rapidity) spanning together a range of $0 < |y| < 2.4$.

The initial state of an inelastic $p\bar{p}$ collision is given by non-perturbative Parton Distribution Functions (PDF's) f which are determined empirically and follow a momentum scale evolution according to QCD. The partonic final state is determined by a convolution of perturbative QCD (pQCD) scattering amplitudes and the PDF's. The cross section for the hard scattering process of partons can be calculated via a perturbative expansion in orders of α_s as

$$\sigma_{\text{pert.}(\alpha_s)} = \sum_n (\alpha_s^n c_n) \otimes f_p(\alpha_s) \otimes f_{\bar{p}}(\alpha_s). \quad (1.1)$$

The pQCD calculations are corrected for non-perturbative effects of hadronisation and underlying event (see Fig. 1). The prediction of the theory can then be expressed as

$$\sigma_{\text{theory}}(\alpha_s) = \sigma_{\text{pert.}}(\alpha_s) \cdot c_{\text{non-pert.}}, \quad (1.2)$$

where the factor $c_{\text{non-pert.}}$ takes into account the non-perturbative corrections. At the same time measurements are corrected for detector effects. Comparisons between measurements and predictions of theory are then accomplished at the hadronic final state [6].

Previous determinations of α_s by means of hadronic jet cross section measurements have had large uncertainties in comparison to other determinations. They have not been very competitive but now the tools for substantial improvements are available. More precise theory calculations together

with more and better measured data lead to smaller uncertainties and competitive results. The jet energy scale has been continuously improved over many years and reaches at present a fractional uncertainty of 1 – 2% over a wide range of jet transverse momenta from 50 GeV to 600 GeV.

Tevatron jet cross section measurements cover a wide kinematic range. In the kinematic plane of momentum fraction x and scale Q^2 unique regions of phase space are covered, in particular when forward jets up to absolute values of pseudorapidity of three are included. There is also overlap with measurements from ep collisions. Therefore the $D\emptyset$ data allow precision tests of pQCD and an independent extraction of α_s .

2. Extraction of α_s

The used perturbative calculations are a sum of a full calculation to order $\mathcal{O}(\alpha_s^3)$ [next-to-leading order (NLO)] combined with $\mathcal{O}(\alpha_s^4)$ resummation of (2-loop) terms from threshold corrections [7]. Adding the 2-loop threshold corrections yields a significant reduction of renormalisation and factorisation scale dependence which in turn leads to significantly smaller uncertainties in the theoretical calculations. These calculations have been ignored for a long time and became only popular and accessible since they are included into fastNLO [11] which provides fast recalculations for arbitrary PDF's and is based on NLOJET++ [12] [13] and code from authors of ref. [7]. The calculations are performed in the $\overline{\text{MS}}$ scheme [8] for five active quark flavours using the next-to-next-to-leading logarithmic (3-loop) solution to the RGE. The PDF's are taken from the MSTW2008 next-to-next-to-leading order (NNLO) parameterisations [9] [10]. The jet transverse momentum is taken for the renormalisation and factorisation scale.

The determination of α_s is accomplished from inclusive jet cross section data points by minimising a χ^2 function between data and theory. The $\alpha_s(p_T)$ values are evolved via the 3-loop solution to the RGE to $\alpha_s(M_Z)$. The central $\alpha_s(M_Z)$ result is obtained by minimising χ^2 with respect to $\alpha_s(M_Z)$ and nuisance parameters for correlated uncertainties.

The procedure described above to determine α_s requires the knowledge of $\sigma_{\text{pert.}}(\alpha_s(M_Z))$ as a continuous function of $\alpha_s(M_Z)$ over a $\alpha_s(M_Z)$ range which covers possible fit results and uncertainties. The MSTW2008 NNLO (NLO) parameterisations are available for 21 different values of $\alpha_s(M_Z)$ in a range of 0.107 - 0.127 (0.110 - 0.130) in steps of 0.001. CTEQ 6.6 parameterisations [14] are available up to NLO for 5 different values of $\alpha_s(M_Z)$. The MSTW2008 PDF's with fine spacing in $\alpha_s(M_Z)$ over a wide range are used together with cubic spline interpolations for the main result.

The $D\emptyset$ inclusive jet production cross section measurement [3] entered already in the MSTW2008 PDF's. The correlations between experimental and PDF uncertainties are not documented. Therefore they can not be taken into account in the extraction of α_s and the cross section data points which provide strong constraints on the PDF's have to be avoided. Precision Tevatron jet data dominate models for gluon densities at high momentum fraction x and start to affect gluon densities at $x \gtrsim 0.25$. At leading order, di-jet events access x values of $x_a = x_T \frac{e^{y_1} + e^{y_2}}{2}$ and $x_b = x_T \frac{e^{-y_1} + e^{-y_2}}{2}$ where x_T is defined by $x_T = \frac{2p_T}{\sqrt{s}}$. The mapping is less unique in inclusive jet production cross section data where the x -value is not fully constrained given a measured bin of p_T and $|y|$. The full kinematics is unknown since it is integrated over the number of jets. The momentum fraction can be approximately constrained in treating the sub-leading jets as central ($|y| = 0$).

The requirement $\tilde{x} < 0.15$ removes all data points for which more than half the cross section is produced at $x_{\max} \gtrsim 0.25$. 22 out of the 110 data points fulfil this requirement (see Fig. 2, left). They are distributed in the kinematic phase space as follows: nine data points in the interval $|y| < 0.4$, $50 < p_T < 145$ GeV; seven data points in the interval $0.4 < |y| < 0.8$, $50 < p_T < 120$ GeV; four data points in the interval $0.8 < |y| < 1.2$, $50 < p_T < 90$ GeV and two data points in the interval $1.2 < |y| < 1.6$, $50 < p_T < 70$ GeV.

The pQCD uncertainties due to uncalculated higher orders are estimated in varying the renormalisation and factorisation scales a factor of two up and down. In the kinematic region used for the extraction of α_s the two scales show positively correlated effects on the cross sections. As a conservative estimate both scales are varied into the same direction simultaneously. The resulting uncertainties can not be treated as Gaussian. Therefore the χ^2 fit is repeated for the scale variations and the differences with respect to the central value of $\alpha_s(M_Z)$ are added in quadrature to the other uncertainties.

3. Results

A combined fit to the 22 selected data points, grouped in nine transverse momentum intervals, yields $\alpha_s(M_Z) = 0.1161^{+0.0041}_{-0.0048}$. The results are shown in Fig. 2 (right) as nine α_s values in the range of $50 < p_T < 145$ GeV with their total uncertainties which are largely correlated among the data points. The results are complemented by DIS jet data from HERA. The $\alpha_s(p_T)$ results obtained here are consistent with the energy dependence predicted by the RGE. The combined result for $\alpha_s(M_Z)$ is consistent with the combination of HERA jet data [15] and the world average [16]. The largest contribution to the total uncertainty comes from the correlated experimental uncertainties which are dominated by jet energy calibration, jet transverse momentum resolution and integrated luminosity.

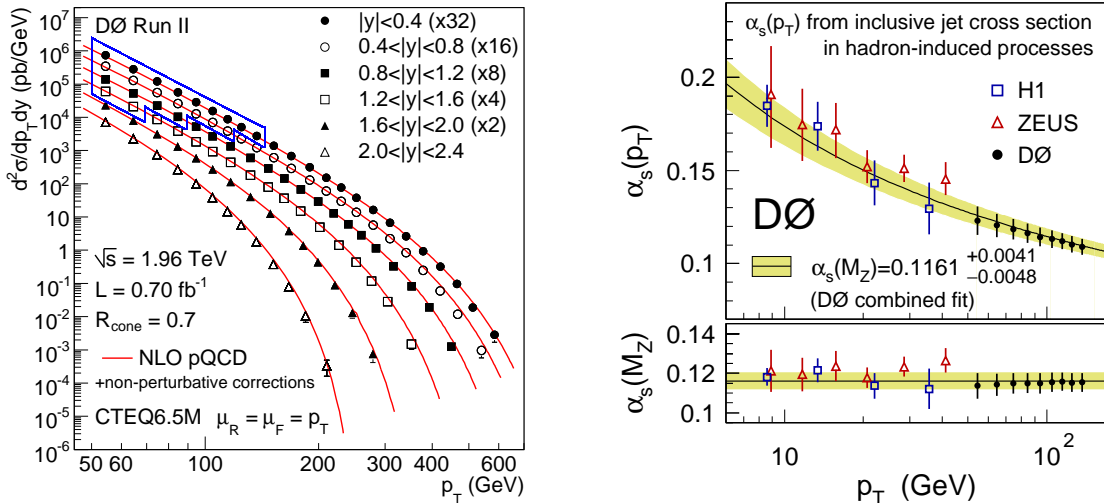


Figure 2: Left: Inclusive double differential jet production cross section measured with the $D\emptyset$ detector [3]. The 22 selected data points for the extraction of α_s are indicated by the surrounding blue polygon.

Right: The strong coupling constant α_s as a function of p_T (top) and at M_Z (bottom). For comparison HERA DIS jet data are superposed. Error bars correspond to total uncertainties.

Variation of the non-perturbative uncertainties by a factor of two up and down changes the central value by +0.0003 and -0.0010. It does not affect the uncertainty of the combined $\alpha_s(M_Z)$ result. Replacing the MSTW2008 NNLO PDF's by the CTEQ 6.6 PDF's increases the central result by only +0.5%, which is much less than the PDF uncertainty. Excluding the 2-loop threshold corrections and using pure NLO pQCD together with the MSTW2008 NLO PDF's and the 2-loop solution to the RGE yields $\alpha_s(M_Z) = 0.1201^{+0.0072}_{-0.0059}$. The small increase in the central value originates from the missing $\mathcal{O}(\alpha_s^4)$ contributions which are compensated by a corresponding increase of α_s . The difference to the central result is well within the scale uncertainty of the NLO result.

4. Conclusions

The strong coupling constant has been determined from the $D\bar{D}$ inclusive jet cross section measurement [3] using theory prediction at NLO with the resummation of 2-loop terms from threshold corrections, i.e. at NNLO accuracy. The $\alpha_s(p_T)$ results are consistent with the predicted energy dependence of the renormalisation group equation. The combined result from 22 selected data points is $\alpha_s(M_Z) = 0.1161^{+0.0041}_{-0.0048}$. This is the most precise result at a hadron collider.

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