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A new determination of α_s
using direct photon production cross sections
in pp and $\bar{p}p$ collisions at $\sqrt{s} = 24.3$ GeV

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Abstract

Direct photon production cross sections obtained in high statistics $\bar{p}p$ and pp collisions at $\sqrt{s} = 24.3$ GeV at the CERN SPS are used in a next-to-leading order QCD analysis. From the cross section difference $\sigma(\bar{p}p \rightarrow \gamma X) - \sigma(pp \rightarrow \gamma X)$ and quark distributions measured in deep inelastic scattering, a determination of the strong coupling constant, α_s , is performed via a measurement of $\Lambda^{(4)}_{\overline{\text{MS}}}$. This measurement yields a value $\Lambda^{(4)}_{\overline{\text{MS}}} = 210 \pm 22(\text{stat.}) \pm 44(\text{syst.})^{+105}_{-36}(\text{theo.})$ MeV. The corresponding value of α_s expressed at M_Z^2 is $\alpha_s(M_Z^2) = 0.1112 \pm 0.0016(\text{stat.}) \pm 0.0033(\text{syst.})^{+0.0077}_{-0.0034}(\text{theo.})$.
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1. Introduction

In a preceding letter [1], we presented direct photon production cross sections in both pp and $\bar{p}p$ interactions at $\sqrt{s} = 24.3$ GeV, covering the kinematic range in transverse momentum $4.1 < p_T < 6.9$ GeV/c ($0.34 < x_T (= 2p_T/\sqrt{s}) < 0.57$) in pp , $4.1 < p_T < 7.7$ GeV/c ($0.34 < x_T < 0.63$) in $\bar{p}p$ and in rapidity $-0.1 < y < 0.9$.

The unique ability of the UA6 experiment to measure direct photons in both pp and $\bar{p}p$ collisions allowed us to compute the difference of the cross sections $\sigma(\bar{p}p \rightarrow \gamma X) - \sigma(pp \rightarrow \gamma X)$ thus isolating the contribution of one leading-order diagram, the annihilation process $q + \bar{q} \rightarrow \gamma + g$. This non-singlet term depends only on the valence-quark distributions and the strong coupling constant. Since the quark distributions are well-measured in deep inelastic scattering (DIS), a direct determination of the coupling constant is therefore possible.

Using the complete higher-order $O(\alpha_s^2)$ QCD calculations of Ref. [2], and structure functions [3] defined beyond leading order obtained from DIS data [4], the QCD scale parameter Λ is determined from the difference of the cross sections. The theoretical calculations now include a NLO correction to bremsstrahlung [5]; this contribution almost cancels in the cross section difference.

The structure function distributions are defined in the $\overline{\text{MS}}$ convention [6], and the QCD scale enters as $\Lambda^{(n_f)}_{\overline{\text{MS}}}$ [7]. The strong coupling constant α_s is related to $\Lambda^{(n_f)}_{\overline{\text{MS}}}$ by [8]:

$$\frac{1}{\alpha_s(\mu^2)} + b' \ln \left(\frac{b\alpha_s(\mu^2)}{1 + b'\alpha_s(\mu^2)} \right) = b \ln \left(\frac{\mu^2}{\Lambda_{\overline{\text{MS}}}^{(n_f)2}} \right), \quad (1)$$

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where

$$b = \frac{33 - 2n_f}{12\pi}, \quad b' = \frac{153 - 19n_f}{24\pi^2 b},$$

μ is the renormalization scale, n_f is the number of flavors (which is four in the kinematic range of this experiment).

Such an approach has already been followed [9] using direct photon cross sections measured by the UA6 collaboration [10]. The new measurements, with smaller systematic uncertainties and approximately a factor of ten (three) increase in integrated luminosity in $\bar{p}p$ (pp) collisions, result in a more precise determination of α_s .

2. The strong coupling constant

2.1. Method

The method [3] involves determining which value of $\Lambda^{(4)}_{\overline{\text{MS}}}$ makes the next-to-leading order (NLO) calculation [2,5] best agree with the measured cross section difference.

Because of the constraints imposed by DIS data, any change in $\Lambda^{(4)}_{\overline{\text{MS}}}$ must be accompanied by corresponding adjustments of the quark distributions. In order to obtain consistent sets of $\Lambda^{(4)}_{\overline{\text{MS}}}$, valence quark, and sea quark distributions, the high statistics DIS data of BCDMS [4] on F_2^p and F_2^p/F_2^n are used. The distribution functions for valence quarks, sea quarks, and gluons are each parametrized at $Q_0^2 = 2$ GeV² and evolved with the prescription of Ref. [11].

For each of several values of $\Lambda^{(4)}_{\overline{\text{MS}}}$ in the range $150 < \Lambda^{(4)}_{\overline{\text{MS}}} < 300$ MeV, a consistent set of quark distribution functions is obtained from NLO QCD fits to the BCDMS data. A constant value $\eta_g = 4.0$ (the best value from Ref. [3]) is used for the gluon distribution,

$$xG(x) = A_g(1-x)^{\eta_g},$$

in all fits, since the valence quark structure functions have negligible sensitivity to this parameter. Acceptable fits to the BCDMS data are possible over the whole range of $\Lambda^{(4)}_{\overline{\text{MS}}}$ used. Indeed, when varying $\Lambda^{(4)}_{\overline{\text{MS}}}$ over this range, the parameters for the quark distributions change by less than their statistical er-

rors as obtained in Ref. [3] when $\Lambda_{\overline{\text{MS}}}^{(4)} = 230$ MeV.

For each of the consistent sets of $\Lambda_{\overline{\text{MS}}}^{(4)}$ and distribution functions obtained above, a theoretical prediction for the cross section difference $\sigma(\bar{p}p \rightarrow \gamma X) - \sigma(pp \rightarrow \gamma X)$ is obtained in the UA6 kinematic range. The values of the factorization scale M and the renormalization scale μ , also needed in the calculation, are the optimized scales [12] determined using the Principle of Minimal Sensitivity (PMS) [8]. In the Drell-Yan process, where the next-to-next-to-leading-logarithm (NNLL) calculations have been performed [13], the use of optimized scales with the NLO calculations yields a reasonable approximation of the NNLL results [14]. An alternative scale-setting procedure, the Fastest Apparent Convergence [15], yields theoretical predictions within $\pm 5\%$ of those obtained with the PMS procedure. For a discussion of theoretical ambiguities due to the choice of scales, see Refs. [12,30].

The fragmentation scale M_F is also needed. It is fixed at $M_F = p_T/2$. The fragmentation function of the photon are taken from Ref. [16].

2.2. The extraction of $\Lambda_{\overline{\text{MS}}}^{(4)}$

The cross section difference $\sigma(\bar{p}p \rightarrow \gamma X) - \sigma(pp \rightarrow \gamma X)$ is given in Ref. [1] for ten values of p_T in the range 4.1 to 7.7 GeV/c (Table 1). For a theoretical prediction characterized by a given value of $\Lambda_{\overline{\text{MS}}}^{(4)}$, a value of the χ^2 between the data and

Table 1

The contribution of each p_T bin to the total χ^2 between the data and the theoretical prediction described in the text and which uses the value of $\Lambda_{\overline{\text{MS}}}^{(4)}$ which best describes the data

p_T range GeV/c	Difference pb/GeV ²	χ^2
4.1–4.3	56.36 ± 7.24	0.21
4.3–4.5	33.58 ± 5.50	0.10
4.5–4.7	24.60 ± 4.11	0.78
4.7–4.9	11.28 ± 3.14	1.92
4.9–5.1	11.84 ± 2.34	0.34
5.1–5.3	6.62 ± 1.78	0.48
5.3–5.7	5.26 ± 0.90	1.91
5.7–6.1	2.01 ± 0.50	0.54
6.1–6.9	0.36 ± 0.21	2.08
6.9–7.7	$0.093^{+0.058}_{-0.052}$	0.21

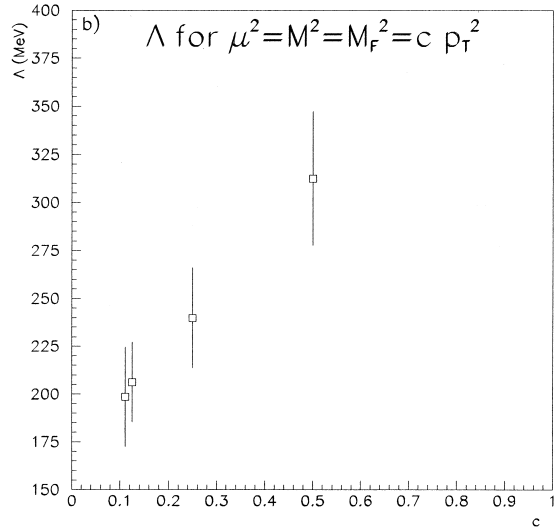
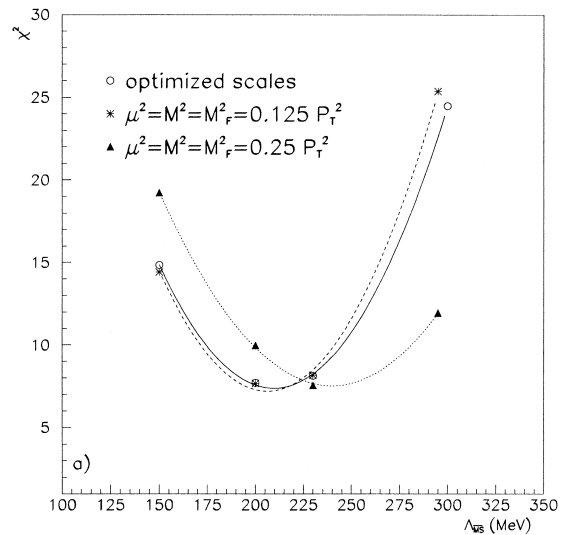


Fig. 1. a) The χ^2 between the theoretical predictions and the measured cross section difference $\sigma(\bar{p}p \rightarrow \gamma X) - \sigma(pp \rightarrow \gamma X)$ as a function of $\Lambda_{\overline{\text{MS}}}^{(4)}$ for various choices of scales. b) Best value of $\Lambda_{\overline{\text{MS}}}^{(4)}$ as a function of the parameter c defining the scales $\mu^2 = M^2 = M_F^2 = cp_T^2$. The error bars are statistical.

the prediction, summed over the ten p_T bins, is calculated. The variation of this χ^2 with $\Lambda_{\overline{\text{MS}}}^{(4)}$ is shown in Fig. 1a. The value of $\Lambda_{\overline{\text{MS}}}^{(4)}$ that best describes the data is taken to be the one yielding the minimum χ^2 . The statistical error on $\Lambda_{\overline{\text{MS}}}^{(4)}$ is taken

to be the change in $\Lambda_{\overline{\text{MS}}}^{(4)}$ corresponding to an increase in χ^2 of 1.0 from the minimum. This procedure yields $\Lambda_{\overline{\text{MS}}}^{(4)} = 210 \pm 22$ MeV which is a considerable improvement in statistical precision over the previous UA6 measurement, $\Lambda_{\overline{\text{MS}}}^{(4)} = 235 \pm 79$ MeV [9]. For the current measurement, the contribution of each data point to the χ^2 is given in Table 1.

2.2.1. Experimental uncertainties

Considering the quadratic sum of the experimental systematic errors of 13%, quoted in [1], as an uncertainty in normalization results in a systematic uncertainty of 44 MeV in $\Lambda_{\overline{\text{MS}}}^{(4)}$. To account for the possibility of point-to-point systematic uncertainties, the χ^2 values were recalculated after adding the statistical and systematic errors in quadrature (an extreme assumption); the result ($\Lambda_{\overline{\text{MS}}}^{(4)} = 203 \pm 27$ MeV) is well within the errors quoted above.

2.3. Theoretical systematic errors

2.3.1. Uncertainties due to the choice of scales

Estimates of the uncertainty on $\Lambda_{\overline{\text{MS}}}^{(4)}$ due to the choice of the factorization scale M , the renormalization scale μ and the fragmentation scale M_F have been made as follows: The results using optimized scales for M and μ are rather insensitive to variation of M_F from $p_T/3$ to $2p_T$ (less than 2% variation in the cross section difference). Appropriate choices for μ are generally limited to $\mu < p_T/2$, where p_T is the largest momentum transfer in the process [17]. Indeed, small second-order terms are found when the scales have low values, increasing to 50% of the Born term when $\mu^2 = M^2 = M_F^2 = p_T^2/2$. Therefore we have repeated the procedure for a conservative range of values of $\mu^2 = M^2 = M_F^2$ between $p_T^2/9$ to $p_T^2/2$. The result, illustrated in Fig. 1b, is that the best fit value of $\Lambda_{\overline{\text{MS}}}^{(4)}$ varies from 198 to 310 MeV. This yields a systematic uncertainty due to uncertainties in the scales of $^{+100}_{-12}$ MeV. The χ^2 curves for two representative values of the scales are compared to the one obtained with the optimized scales in Fig. 1a.

As a cross check of the calculation used in this paper, another NLO calculation of direct photon production which uses a Monte Carlo approach but without the NLO bremsstrahlung corrections [18]

reproduces the same cross sections when all scales are fixed to $p_T/2$.

2.3.2. Uncertainties due to the choice of parton distribution functions

The effect of using different structure functions has been tested by repeating the above analysis for three sets of structure functions, ABFOW [3], CTEQ4 [19] and MRS98 [20] at a fixed scale of $\mu = M = M_F = p_T/2$. The results were $\Lambda_{\overline{\text{MS}}}^{(4)} = 240$ MeV for ABFOW, $\Lambda_{\overline{\text{MS}}}^{(4)} = 255$ MeV for CTEQ4 and $\Lambda_{\overline{\text{MS}}}^{(4)} = 271$ MeV for MRS98, as shown in Fig. 2. We therefore estimate the systematic uncertainty on $\Lambda_{\overline{\text{MS}}}^{(4)}$ due to structure function choice to be ± 30 MeV.

It has recently been shown that taking into account nuclear binding in the deuteron leads to a possible increase in the d quark distribution function [21,22]. The role of the d quark is relatively minor in direct photon production since the cross section is proportional to the square of the charge of the participating quark. Nevertheless, we note that the d content in MRS98 is up to 46% larger than that in CTEQ4M. We conclude that the effect of any rea-

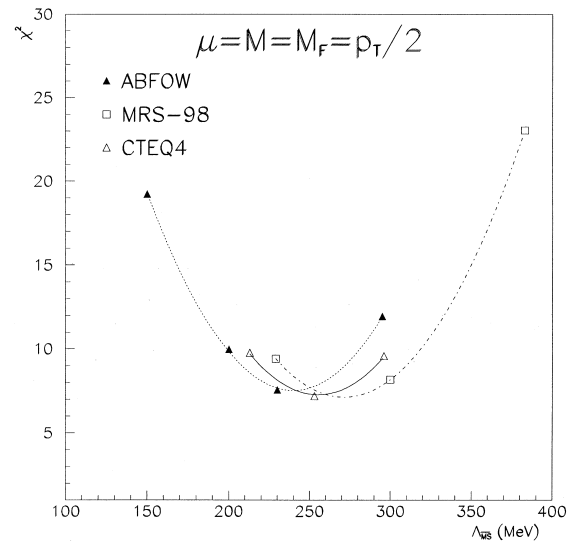


Fig. 2. The χ^2 between the theoretical predictions and the measured cross section difference $\sigma(\bar{p}p \rightarrow \gamma X) - \sigma(pp \rightarrow \gamma X)$ as a function of $\Lambda_{\overline{\text{MS}}}^{(4)}$ for various choices of the quark distribution.

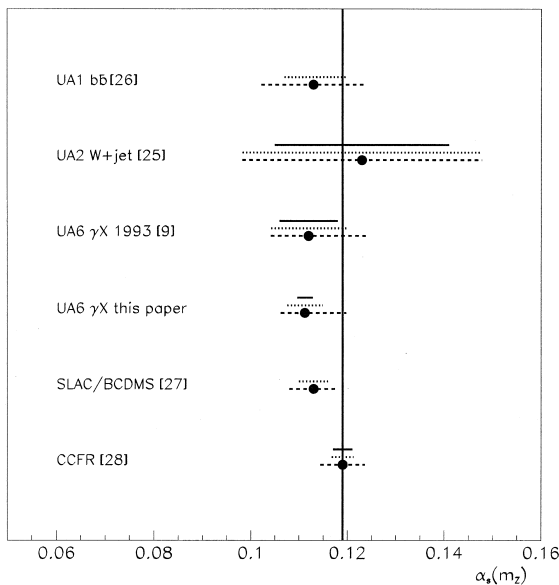


Fig. 3. Comparison of this determination of α_s to some other NLO determinations in high energy hadro-production of W + jet [25], $b\bar{b}$ [26] and from scaling violation in deep inelastic scattering with electrons and muons [27] and with neutrinos [28]. The statistical (full), total experimental including systematics (dotted) and overall (experimental and theoretical added in quadrature) (dashed) uncertainties are shown. The world mean value [29] is shown as a vertical line.

sonable increase in the d quark distribution is already taken into account by the ± 30 MeV systematic uncertainty we have assigned to the choice of input structure functions.

Varying the value of η_g in the range $3 < \eta_g < 5$ changes the calculated value of $\Lambda^{(4)}_{\overline{\text{MS}}}$ by ± 17 MeV.

2.3.3. Overall theoretical uncertainty

The overall theoretical uncertainty on $\Lambda^{(4)}_{\overline{\text{MS}}}$, $^{+105}_{-36}$ MeV, is obtained by combining quadratically the uncertainties due to scales and to parton distribution functions.

3. Results

The resulting value of $\Lambda^{(4)}_{\overline{\text{MS}}}$ is 210 ± 22 (stat.) ± 44 (syst.) $^{+105}_{-36}$ (theo.) MeV. The corresponding value of α_s , expressed at M_Z^2 , is $\alpha_s(M_Z^2) = 0.1112 \pm 0.0016$ (stat.) ± 0.0033 (syst.) $^{+0.0077}_{-0.0034}$ (theo.).

The extrapolation to M_Z^2 involves increasing n_f from 4 to 5 due to the b-quark threshold. This results in an additional uncertainty of ± 0.001 on α_s [23,24] which is included in the theoretical error.

We compare this result to some other determinations at NLO, in high energy hadron-hadron collisions [25,26] and in deep inelastic scattering [27,28] in Fig. 3, where the experimental and theoretical uncertainties are both shown. The mean world value shown in the figure is taken from a recent summary of α_s determinations [29].

4. Conclusions

From the difference of cross sections $\sigma(\bar{p}p \rightarrow \gamma X) - \sigma(pp \rightarrow \gamma X)$, $\Lambda^{(4)}_{\overline{\text{MS}}}$ is measured to be 210 ± 22 (stat.) ± 44 (syst.) $^{+105}_{-36}$ (theo.) MeV, in very good agreement with the determination from scaling-violation analyses in deep inelastic scattering. The corresponding value of α_s expressed at M_Z^2 is $\alpha_s(M_Z^2) = 0.1112 \pm 0.0016$ (stat.) ± 0.0033 (syst.) $^{+0.0077}_{-0.0034}$ (theo.). This new determination of α_s approaches the precision achieved in deep inelastic scattering experiments.

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