Determination of α_s and the gluon distribution using direct photon production in $\bar{p}p$ and pp collisions

UA6 Collaboration

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Abstract

Direct photon cross sections obtained in $\bar{p}p$ 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 $\Lambda_{\overline{MS}}^{(4)}$. This first measurement of $\Lambda_{\overline{MS}}^{(4)}$ using direct photon data yields a value $\Lambda_{\overline{MS}}^{(4)} = 235 \pm 79 (stat.) \pm 70 (syst.)$ MeV. The corresponding value of α_s , expressed at M_Z^2 is $\alpha_s(M_Z^2) = 0.112 \pm 0.006 (stat.) \pm 0.005 (syst.) \pm_{0.001}^{0.009} (theo.)$. The gluon distribution in the proton for $x > 0.2$ is determined both from the $\bar{p}p$ and from the pp data, and the results agree with each other and with previous determinations.

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1 Introduction

Hadronic cross sections for direct photon production strongly constrain the gluon distribution in the nucleon [1]. This sensitivity is due to the importance of the leading-order QCD Compton process $q + g \rightarrow \gamma + q$ (Fig. 1a). In contrast, deep inelastic scattering (d.i.s.) is sensitive to the gluon structure function only through higher order diagrams.

In the preceding letter [2], we presented direct photon cross sections in both pp and $\bar{p}p$ interactions at $\sqrt{s} = 24.3$ GeV, covering the kinematic range in transverse momentum $4.1 < p_T < 6.1$ GeV/c ($0.34 < x_T < 0.50$) and rapidity $-0.2 < y < 1.0$. From these measurements, we determine the gluon distribution in the proton for $x > 0.2$. The unique ability of the UA6 experiment to measure direct photons in both pp and $\bar{p}p$ collisions allows 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 the other leading-order diagram, the annihilation process $q + \bar{q} \rightarrow \gamma + g$ (Fig. 1b). This non-singlet term depends only on the valence-quark distributions and the strong coupling constant. Since the quark distributions are well-measured in d.i.s., a direct determination of the coupling constant is therefore possible.

Using the complete higher-order $O(\alpha_s^2)$ QCD calculations of Ref. [3], and structure functions [1] defined beyond the leading order obtained from d.i.s. data [4], the QCD scale parameter Λ is determined from the difference of the cross sections. The structure function distributions are defined in the $\overline{MS}$ convention [5], and the QCD scale enters as $\Lambda_{\overline{MS}}^{(n_f)}$ [6]. The strong coupling constant α_s is related to $\Lambda_{\overline{MS}}^{(n_f)}$ by [7]:

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

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 (taken to be four), and α_s is the numerical solution of equation (1).

The gluon distribution in the proton is determined from the individual cross sections in pp and $\bar{p}p$.

Such an approach was first attempted using direct photon cross sections obtained in π^-p and π^+p collisions, but had less sensitivity to $\Lambda_{\overline{MS}}^{(4)}$ due to the uncertainty in the valence quark structure functions of the pion [8].

2 The strong coupling constant

2.1 Method

The method [1] involves determining which value of $\Lambda_{\overline{MS}}^{(4)}$ makes the next-to-leading order (NLO) calculation [3] best agree with the experimental data on the cross-section difference. However because of the constraints imposed by d.i.s. data, any change in $\Lambda_{\overline{MS}}^{(4)}$ must be accompanied by corresponding adjustments of the quark and gluon distributions. In order to obtain consistent sets of $\Lambda_{\overline{MS}}^{(4)}$, valence quark, sea quark, and gluon distributions, the high statistics d.i.s. 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. In particular, the gluon distribution is parametrized as

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

and depends on only one parameter, η_g (A_g is determined by the momentum sum rule). Using this parametrization, values of $\eta_g = 4.0$ and $\Lambda_{\overline{MS}}^{(4)} = 230$ MeV were obtained by ABFOW [1] by simultaneously fitting direct photon data and the BCDMS d.i.s. data [4].

For each of several values of $\Lambda_{\overline{MS}}^{(4)}$ in the range $150 < \Lambda_{\overline{MS}}^{(4)} < 300$ MeV, a consistent set of quark distribution functions is obtained from NLO QCD fits to the BCDMS data. The value of η_g is left unchanged at 4.0 throughout, 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 $\Lambda_{\overline{MS}}^{(4)}$ used. Indeed, when varying $\Lambda_{\overline{MS}}^{(4)}$ over this range, the parameters for the quark distributions change by less than their statistical errors as obtained in Ref. [1] when $\Lambda_{\overline{MS}}^{(4)}$ is set at 230 MeV.

For each of the consistent sets of $\Lambda_{\overline{MS}}^{(4)}$ 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 [9] determined using the Principle of Minimal Sensitivity (PMS) [7]. An alternative scale-setting procedure, the Fastest Apparent Convergence [10], 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. [9] and [1].

2.2 Results

The cross section difference $\sigma(\bar{p}p \rightarrow \gamma X) - \sigma(pp \rightarrow \gamma X)$ is given in Ref. [2] for six values of p_T in the range 4.1 to 6.1 GeV/c (Table 1). For a given theoretical prediction, characterized by a given value of $\Lambda_{\overline{MS}}^{(4)}$, a value of the χ^2 between the data and the prediction, summed over the six p_T bins, is obtained. The variation of this χ^2 with $\Lambda_{\overline{MS}}^{(4)}$ is shown in Fig. 2. The value of $\Lambda_{\overline{MS}}^{(4)}$ that best describes the data of Ref. [2] is then taken to be that characterizing the theoretical prediction which yields the minimum χ^2 . The statistical error on $\Lambda_{\overline{MS}}^{(4)}$ is taken to be the change in $\Lambda_{\overline{MS}}^{(4)}$ corresponding to an increase in χ^2 of 1.0 from the minimum. This procedure yields $\Lambda_{\overline{MS}}^{(4)} = 235 \pm 79$ MeV. Considering the quadratic sum of the experimental systematic errors of 21%, quoted in [2], as an uncertainty in normalization results in a systematic uncertainty of 70 MeV in $\Lambda_{\overline{MS}}^{(4)}$. 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 is well within the errors quoted above.

Estimates of the effects of the uncertainty in the factorization scale M and the renormalization scale μ have been made in the following three ways. First, the range of variation in the best-fit values of $\Lambda_{\overline{MS}}^{(4)}$ is from 226 MeV when $\mu^2 = M^2 = p_T^2/8$ to 381 MeV when $\mu^2 = M^2 = 3p_T^2/4$. With the scales set to higher values it is not possible to find a minimum within the range of $\Lambda_{\overline{MS}}^{(4)}$ values which maintain a reasonable fit to the d.i.s. data. However, the variation of χ^2 becomes slower around the minimum obtained by extrapolating the d.i.s. parameters, such that for example with $\mu^2 = M^2 = .875 p_T^2$, $\Lambda_{\overline{MS}}^{(4)} = 447 \pm 157$ MeV. Second, performing a decoupled fit, in which $\Lambda_{\overline{MS}}^{(4)}$ in the structure function evolution is fixed to, for example, 230 MeV, and $\Lambda_{\overline{MS}}^{(4)}$ in the evaluation of α_s is left free, leads to a minimum χ^2 at $\Lambda_{\overline{MS}}^{(4)} = 489$ MeV when $\mu^2 = M^2 = p_T^2$, a value incompatible with the d.i.s. data. Finally, setting $\mu^2 = M^2 = K p_T^2$ with K as a free parameter which is adjusted to give the best fit to the data, results in a large correlation between the two parameters. The minimum χ^2 spans a broad range of the parameters. For example, when K is fixed to 0.26, $\Lambda_{\overline{MS}}^{(4)} = 263_{-90}^{+84}$ MeV while when $\Lambda_{\overline{MS}}^{(4)}$ is fixed to 263 MeV, $K = 0.26_{-0.135}^{+0.50}$, where the lower error corresponds to the lowest value that can

be probed with $Q_0^2 = 2 \text{ GeV}^2$.

It is expected that μ should generally be at least a factor of two smaller than the largest momentum transfer in the process [13]. Indeed, small second-order terms are found when the scales have low values. The effect of the scale uncertainty is quoted as $^{+146}_{-9}$ MeV around the value obtained with optimized scales for a variation of the scales from $\mu^2 = M^2 = p_T^2/8$ to $\mu^2 = M^2 = 3p_T^2/4$. In the Drell-Yan process, where the next-to-next-to-leading-logarithm (NNLL) calculations have been performed [11], the use of optimized scales with the NLO calculations yields a reasonable approximation of the NNLL results [12].

The result of this direct determination, $\Lambda_{\overline{MS}}^{(4)} = 235 \pm 79 (stat.) \pm 70 (syst.)^{+146}_{-9} (theo.)$ MeV, where the first error is statistical, the second is the experimental systematic uncertainty, and the third is an estimate of the uncertainty due to scale ambiguities, is in good agreement with the value $\Lambda_{\overline{MS}}^{(4)} = 263 \pm 42 (stat. + syst.) \pm 55 (scale)$ MeV, obtained [14] from an analysis of scaling violations in high statistics d.i.s. data from SLAC [15] and the BCDMS collaboration [4].

3 The gluon distribution

The method used to extract a gluon distribution is similar to that used for the extraction of $\Lambda_{\overline{MS}}^{(4)}$: consistent sets of $\Lambda_{\overline{MS}}^{(4)}$ and quark distributions are obtained from fits to the BCDMS data but this time for several values of η_g in the range $3.0 < \eta_g < 5.5$. Theoretical predictions of the $\bar{p}p \rightarrow \gamma X$ and $pp \rightarrow \gamma X$ cross sections for each of the sets are computed and χ^2 values between the data and each of the predictions, summed over the six p_T bins, are calculated.

The variation of χ^2 as a function of η_g is shown in Fig. 3 for the $\bar{p}p$ and pp data separately. The values of η_g which best match the data are determined from the minima of the two curves. They are $\eta_g = 3.3 \pm 0.4 \pm 0.6$ for pp and $\eta_g = 3.2 \pm 0.7 \pm 1.0$ for $\bar{p}p$. The first error is statistical, and the second corresponds to the estimated systematic error in the cross sections ($\pm 20\%$ for pp and $\pm 15\%$ for $\bar{p}p$ [2]). The use of optimized scales results in small second-order terms, in contrast to the use of $\mu^2 = M^2 = p_T^2$. We have therefore limited this analysis to the use of the optimized scales. The analysis of the whole UA6 direct photon sample, with integrated luminosities increased above those used here by a factor of about three in pp and about ten in $\bar{p}p$ reactions, which is currently in progress, should warrant a more detailed study of the theoretical uncertainties.

The values of η_g found are in very good agreement with each other and with the value obtained in [1] using direct photon data in the fixed-target energy range [16, 17, 18]. The gluon distribution obtained from the pp data is shown in Fig. 4 at $Q^2 = 5 \text{ GeV}^2$ to be compared to the results from deep inelastic scattering [4] and from a recent global determination of structure functions (MRS-D0) [19].

4 Conclusions

From the difference of cross sections $\sigma(\bar{p}p \rightarrow \gamma X) - \sigma(pp \rightarrow \gamma X)$, $\Lambda_{\overline{MS}}^{(4)}$ is measured to be $235 \pm 79 (stat.) \pm 70 (syst.)^{+146}_{-9} (theo.)$ MeV, value in very good agreement with the determination from scaling-violation analysis in deep inelastic scattering. The corresponding value of α_s expressed at M_Z^2 is $\alpha_s(M_Z^2) = 0.112 \pm 0.006 (stat.) \pm 0.005 (syst.)^{+0.009}_{-0.001} (theo.)$, where the theoretical error is quoted for a variation of the scales from $p_T^2/8$ to $3p_T^2/4$. This is in good agreement with the value [21] obtained by the LEP collaborations.

Assuming a gluon distribution of the form $xG(x, Q_0^2) = A_g(1-x)^\eta$ at $Q_0^2 = 2 \text{ GeV}^2$, the value of η_g is $3.3 \pm 0.4 \pm 0.6$ from inclusive direct-photon production in pp collisions

and $3.2 \pm 0.7 \pm 1.0$ in $\bar{p}p$ collisions.

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p_T range GeV/c	$\langle \sigma(\bar{p}p \rightarrow \gamma X) \rangle$ pb/GeV ²	$\langle \sigma(pp \rightarrow \gamma X) \rangle$ pb/GeV ²	Difference pb/GeV ²
4.1–4.3	$119.1 \pm 21.8 (\pm 17.9)$	$55.5 \pm 13.7 (\pm 11.1)$	$63.6 \pm 25.7 (\pm 13.4)$
4.3–4.5	$66.6 \pm 15.1 (\pm 10.0)$	$28.9 \pm 8.8 (\pm 5.8)$	$37.7 \pm 17.5 (\pm 7.9)$
4.5–4.7	$44.6 \pm 10.8 (\pm 6.7)$	$16.3 \pm 6.6 (\pm 3.3)$	$28.3 \pm 12.7 (\pm 5.9)$
4.7–4.9	$26.8 \pm 8.1 (\pm 4.0)$	$9.6 \pm 4.8 (\pm 1.9)$	$17.2 \pm 9.4 (\pm 3.6)$
4.9–5.3	$7.7 \pm 3.5 (\pm 1.2)$	$6.0 \pm 2.0 (\pm 1.2)$	$1.7 \pm 4.0 (\pm 0.4)$
5.3–6.1	$5.4 \pm 1.4 (\pm 0.8)$	$1.5 \pm 0.5 (\pm 0.2)$	$4.3 \pm 1.5 (\pm 0.9)$

Table 1: The average ($-0.2 < y < 1.0$) invariant cross sections $\sigma(\bar{p}p \rightarrow \gamma X)$ and $\sigma(pp \rightarrow \gamma X)$, and the difference $\sigma(\bar{p}p \rightarrow \gamma X) - \sigma(pp \rightarrow \gamma X)$ of Ref. [2] as a function of p_T . The statistical errors and the estimated systematic errors (in parentheses) are also given.

Figure 1: The Born diagrams for direct photon production: a) QCD Compton $qg \rightarrow q\gamma$
b) annihilation $q\bar{q} \rightarrow g\gamma$.

Figure 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 $\Lambda_{\overline{MS}}^{(4)}$.

Figure 3: The χ^2 between the theoretical predictions and the measured cross sections $\sigma(\bar{p}p \rightarrow \gamma X)$ and $\sigma(pp \rightarrow \gamma X)$ as a function of η_g . The corresponding variations of $\Lambda_{\overline{MS}}^{(4)}$ and A_g with η_g are also shown.

Figure 4: The gluon distribution at $Q^2 = 5 \text{ GeV}^2$ obtained from the pp data: the shaded area corresponds to the 1σ statistical uncertainty and the dotted lines are after linear addition of the 1σ systematic uncertainty on the experimental data. The solid line is the gluon distribution from a recent global determination of structure functions (MRS-D0) [19] as implemented in [20]. The data points (statistical errors only) come from a singlet next-to-leading order analysis of deep inelastic scattering data (BCDMS) [4].