Measurement of the strong coupling constant α_s in W-boson production at the CERN proton-antiproton collider

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The strong coupling constant α_s has been determined from a study of the reaction $\bar{p}p \to W^{\pm}X$, $W \to e\nu$ at $\sqrt{s}$ of 630 GeV in the UA1 experiment at CERN. The measurement is based upon a study of jet production in association with W bosons. The result obtained is $\alpha_s(M_W^2)=0.127\pm0.026(\text{stat})\pm0.034(\text{syst})$.

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I. INTRODUCTION

The measurement of the strong coupling constant α_s in different processes provides one of the most important quantitative tests of QCD, the present theory of strong interactions. In recent years α_s has been determined from hadronic cross sections and jet production in e^+e^- annihilation, from quarkonium decay rates, and from scaling violations in deep-inelastic leptoproduction [1].

In hadron-hadron interactions the W,Z production process offers the cleanest means of measuring α_s. W,Z production cross sections are in excellent agreement with electroweak-QCD predictions [2]. In the absence of QCD corrections the production of a $W^{\pm}$ boson is described by the Drell-Yan mechanism. The strong interaction accounts for corrections which result in the production of hadronic jets in association with the $W^{\pm}$. At CERN energies these have been shown to originate from initial-state gluon radiation [3]. Thus, the cross-section ratio $R=\sigma_1/\sigma_0$ for $W+1$ jet to $W+0$ jet production depends on the strong coupling constant α_s.

This paper describes a measurement of α_s at $Q^2 \approx M_W^2$ in the reaction $\bar{p}p \to W^{\pm}X$, $W \to e\nu$ at $\sqrt{s}$ of 630 GeV in the UA1 experiment at CERN. The strong coupling constant is determined by comparing the experimental and Monte Carlo estimates of $R(\alpha_s)$ using the same procedure as that employed by the UA2 experiment for a similar measurement [4].

II. DATA

The relative production rates of 0 and 1 jet events were studied in the sample of 295 $W \to e\nu$ decays accumulated by UA1 between 1982 and 1985. This corresponds to a total integrated luminosity of 768 nb^{-1} at center-of-mass energies of $\sqrt{s}=546$ and 630 GeV. The identification of $W \to e\nu$ events in the UA1 detector has been described in detail in previous publications [5]. Here we discuss only the features of the detector and W selection relevant to this analysis.

Jets were identified by the standard UA1 jet-finding algorithm [6] using a minimum jet transverse-energy initiator of 2.5 GeV. A requirement of jet transverse energy $E_T \geq 10.0$ GeV was imposed on the jets to minimize contamination from jets associated with beam fragments and to ensure efficiency in the jet identification. Figure 1

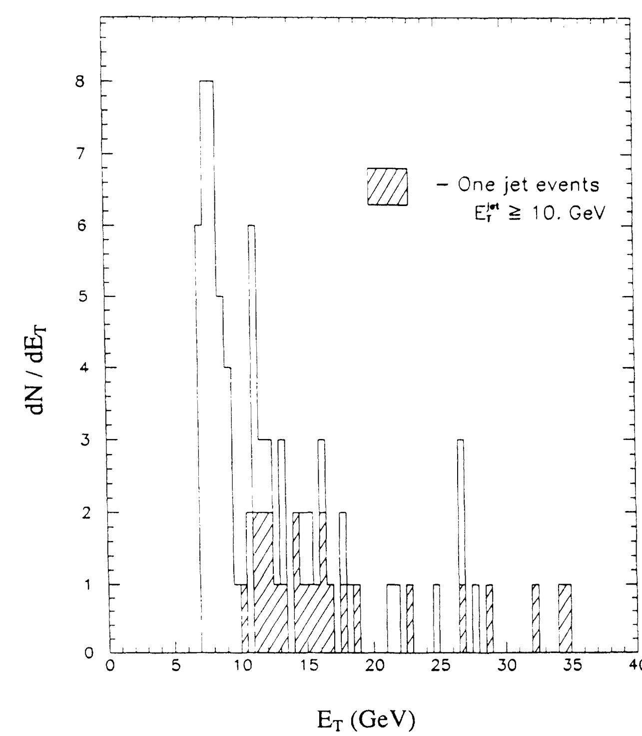

FIG. 1. E_T distribution for jets with $E_T > 7.0$ GeV in the $W \to e\nu$ data sample. The shaded region corresponds to the $W+1$-jet events with $E_T \geq 10.0$ GeV (see text).

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shows the resulting E_T distribution for all jets in the W sample with $E_T \geq 7.0$ GeV. With the above jet definition there are 262 events with no jets, 25 events with one jet, and 8 events with two or more jets.

The calculation of the number of background events due to fluctuations in QCD hard-scattering events is discussed in detail in [5]. This indicates that $W \rightarrow e\nu$ events in which the missing transverse energy is within 4 standard deviations of zero are overwhelmingly due to QCD background. This consideration leads a background estimate of 8.2 events for the data sample used here. Assuming that the background is independent of event topology leads to background estimates of 6.5 ± 1.4 and 0.9 ± 0.5 events for the 0 and 1 jet samples, respectively. Additional details of the background calculation can be found in Ref. [7]. After background subtraction there are 255.5 ± 16.2 jetless events and 24.1 ± 5.0 events with one reconstructed jet. The observed production ratio R_{expt} is then

$$R_{\text{expt}} = N_1/N_0 = 0.094\pm0.020 ,$$

where N_1 is the number of events containing a W and one jet and N_0 is the number of events containing a W and zero jets.

III. α_s ESTIMATE

The value of α_s can be determined by comparing experimental and Monte Carlo estimates of the ratio R and varying the value of α_s until $R_{\text{MC}}(\alpha_s) = R_{\text{expt}}$. Since the precision of the final result relies on the accuracy of the calculation of R_{MC} we give a detailed description of the Monte Carlo simulation and its uncertainties below.

The Ellis-Kleiss-Stirling (EKS) Monte Carlo program [8] was used to generate W production in parton-parton collisions. It uses the matrix elements of all tree-level diagrams for W production to order α_s^2 to generate final states consisting of a W boson and zero, one, or two outgoing partons. The corresponding parton cross sections diverge for certain event configurations due to the lack of loop diagrams. To control these we introduce cutoffs on the parton transverse momentum P_T^{min} and on the angular separation of the outgoing partons, ω^{min}.

The effects of the missing loop diagrams and of the cutoffs are corrected with multiplicative "K factors" defined in Eq. (1). To do this we have used the procedure developed by UA2 [4,9]. In this approach K_0 is calculated exactly, K_1 is calculated approximately, and K_2 is trivially unity. The major difference between this calculation and that of Ref. [4] is the use of the next-to-leading-order Martin-Roberts-Stirling set B (MRSB) parton distribution parametrizations [10] in the EKS Monte Carlo program.

The value of α_s used in the Monte Carlo generation, α_s^{MC}, was fixed at 0.136 through the choice of the MRSB parton distributions with $\Lambda_{\overline{\text{MS}}} = 200$ MeV and the conventional choice of $Q^2 = M_W^2$ for the Q^2 scale. ($\overline{\text{MS}}$ denotes the modified minimal-subtraction scheme.)

Event samples of W events containing zero, one, and two outgoing partons were generated with the EKS Monte Carlo calculation using cutoff values of $P_T^{\text{min}} = 7.0$ GeV/c and $\omega^{\text{min}} = 20°$. The ISAJET Monte Carlo program [11] was used to hadronize the partons from the EKS generator and to add the residual beam fragments or underlying event. The resulting 9000 simulated events were then processed through full detector simulation and event reconstruction, and subjected to the selection criteria used for the experimental data.

It should be emphasized that the number of Monte Carlo jets satisfying the selection criteria in Sec. II do not, in general, match the number of outgoing partons generated in the EKS simulation. For example, the parton E_T may fall below the jet E_T threshold of 10 GeV or an additional jet may occur in the underlying event. Thus, each group of Monte Carlo events (0,1,2 partons) feeds into all three jet categories (see Table I) and the number of reconstructed events containing j jets, N_j, is given by

$$N_j = \sum_{p=0}^{2} K_p N_{pj} ,$$

where N_{pj} is the number of events generated with p final-state partons and j reconstructed jets and K_p is the corresponding K factor. Thus, the Monte Carlo ratio of $W+1$ jet events/$W+0$ jet events, R_{MC}, is given by

$$R_{\text{MC}} = \frac{K_0 N_{01} + K_1 N_{11} + K_2 N_{21}}{K_0 N_{00} + K_1 N_{10} + K_2 N_{20}} = 0.013\pm0.004 , \tag{1}$$

where the calculated correction factors K are $K_0 = 1.09$, $K_1 = 1.34$, and $K_2 = 1$.

The most direct method of determining α_s would be to repeat the entire Monte Carlo generation for different values of α_s^{MC} and then interpolate to find the value at which $R_{\text{MC}} = R_{\text{expt}}$. Since this procedure would be prohibitive in computer time, we have extrapolated $R_{\text{MC}}(\alpha_s)$ with the $O(\alpha_s)$ expansions

$$\begin{aligned} N_{pj}(\alpha_s) &= r^p N_{pj}(\alpha_s^{\text{MC}}) , \\ K_0(\alpha_s) &= 1 + r[K_0(\alpha_s^{\text{MC}}) - 1] , \\ K_1(\alpha_s) &= 1 + r[K_1(\alpha_s^{\text{MC}}) - 1] , \end{aligned} \tag{2}$$

where $r = \alpha_s/\alpha_s^{\text{MC}}$. The value of α_s for which $R_{\text{MC}}(\alpha_s) = R_{\text{expt}}$ is then

$$\alpha_s = 0.127\pm0.026 ,$$

where the error is statistical only.

TABLE I. Summary of the number of reconstructed jets found in W event samples generated with zero, one, and two additional final-state partons (see text). The minimum parton and jet E_T cuts were 7.0 and 10 GeV, respectively.

	Number of events reconstructed		
	$W+0$ jet	$W+1$ jet	$W+2$ jet
$W+0$ partons generated	1288	3	0
$W+1$ partons generated	1631	753	24
$W+2$ partons generated	173	448	146

IV. SYSTEMATIC ERRORS

To complete the measurement we consider the systematic uncertainties which contribute to the error on α_s.

(i) Jet definition. To search for possible systematic effects we investigated the effect of varying each of the parameters of the UA1 jet algorithm in turn: the minimum initiator E_T from 1.5 to 3.0 GeV; the jet cone size, $\Delta R = \sqrt{(\Delta\phi^2 + \Delta\eta^2)}$, between 0.7 and 1.3; and $E_T^{\min}$ between 9.0 and 15.0 GeV. In each case the observed change in α_s is compatible with statistical fluctuations with no indication of any systematic effect.

(ii) Absolute energy calibration. The effect of the uncertainty in the absolute energy scale was studied by varying the jet energy $\pm 8\%$ in the Monte Carlo data. The corresponding change in α_s is $\Delta\alpha_s = \pm 0.015$.

(iii) Choice of parton distributions. To estimate the uncertainty associated with the choice of parton distribution functions, we compare the values of α_s calculated using the MRSB and MRSE structure functions. These are representative of the range of uncertainty allowed by present experimental data. The corresponding error estimate is $\Delta\alpha_s = \pm 0.013$.

(iv) Underlying event simulation. The influence of the underlying event is expected to be small because of the relatively high-$E_T^{\min}$ cut used in jet definition. To study it we have varied the mean value of the transverse momentum in the underlying event by $\pm 25\%$. This leads to an uncertainty in α_s of ± 0.005.

(v) Fragmentation model. We have varied the average transverse momentum of the fragmenting particles with respect to the original parton direction by ± 0.10 GeV around the nominal ISAJET value of 0.35 GeV. The corresponding uncertainty is $\Delta\alpha_s = \pm 0.010$.

(vi) K factors. Since the EKS generator is based on an incomplete second-order calculation and includes no third- or higher-order contributions, some uncertainties in the K factors must result. While the magnitude of these uncertainties is unknown, the effect on the measured value of α_s can be estimated. To do this we have used three different approaches.

First we varied the K factors directly through the addition of second-order terms in expansion (2) used to vary $R_{\rm MC}$

Second, using the analysis of [12] as a guide, we have assumed an uncertainty of approximately $\pm 10\%$ in K_0 and K_1, and calculated the corresponding shift in the α_s value.

Last, K_1 depends on the values of both cutoff parameters ($\omega^{\min}$ and $P_T^{\min}$) so that the uncertainties in their values are directly reflected into the uncertainties in K_1. We have studied this by varying $\omega^{\min}$ and $P_T^{\min}$ over substantial ranges about their nominal values (10°–40° for $\omega^{\min}$ and 4–12 GeV/c for $P_T^{\min}$). The changes in $\omega^{\min}$ produce no measurable change in α_s. However, by varying $P_T^{\min}$ we find that the value of α_s rises with increasing $P_T^{\min}$ approximately as $\delta\alpha_s/\delta P_T^{\min} = 0.004$ GeV^{-1}. The reason for this increase is unclear and cannot be ascribed to statistical fluctuations.

Each of the three studies leads to a similar systematic uncertainty in α_s from which we estimate a total uncertainity due to the K-factor calculations of $\Delta\alpha_s = \pm 0.025$.

(vii) Total systematic uncertainty. By combining all of the above errors in quadrature, we arrive at a total systematic uncertainty of

$$\Delta\alpha_s(\text{syst}) = \pm 0.034 ,$$

where the error is dominated by the uncertainty on the K factors.

V. SUMMARY

We have measured the value of the strong coupling constant α_s in a study of the associated production of W bosons and jets in proton-antiproton interactions at $\sqrt{s}$ of 630 GeV. The coupling constant is determined by comparing experimental and Monte Carlo estimates of $R(\alpha_s)$, the cross-section ratio σ_1/σ_0 for $W+1$ jet and $W+0$ jet production. We obtain

$$\alpha_s = 0.127 \pm 0.026(\text{stat}) \pm 0.034(\text{syst})$$

for an energy scale of $Q^2 \approx M_W^2$, where the systematic error arises mainly from the omission of QCD loop diagrams in the Monte Carlo calculation. The result is in good agreement with other recent measurements from $p\bar{p}$ [13] and e^+e^- interactions [14] at the same Q^2 scale, and with previous measurements at lower values of Q^2 for $\Lambda_{\overline{\rm MS}}$ in the range 200–300 MeV [15].

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