Search for $W \to c\bar{s}$, $Z \to c\bar{c}, b\bar{b}$ in muon-jet events at the CERN proton-antiproton collider

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A search for quark decays of the W and Z particles produced in proton-antiproton collisions at $\sqrt{s}$ of 630 GeV in the UA1 experiment at the CERN collider is described. The search was made in the channels $W \to c\bar{s}$, $Z \to c\bar{c}, b\bar{b}$ where b and c quarks were identified by the presence of a high-p_T muon in or near a jet. Although these decay channels avoid the copious background of QCD produced light quark and gluon jets, it was not possible to detect a W or Z signal because of the large cross section for strong $c\bar{c}$ and $b\bar{b}$ production.

The W and Z bosons were first observed at the CERN $p\bar{p}$ collider through their electronic and muonic decay modes.[1] Subsequently the UA1 experiment reported observation of the decay $W \to \tau\nu$ (Ref. 2). The measured cross sections times branching ratio, σB, for production and leptonic decay of W and Z are in good agreement with the predictions of standard model.[3]

In the standard model the color degree of freedom ensures that the dominant decay modes of W and Z are to quark-antiquark; the exact ratio of $\Gamma(q\bar{q})$ to $\Gamma(\text{tot})$ depends on the mass of the top quark but is always above $\frac{2}{3}$.

It is important to observe the decay of W or Z to quarks in order to confirm this aspect of the standard model. Furthermore, it is anticipated that multijet spectroscopy will be an important tool at present and future colliders; W or Z jet decays could provide a mass calibration for this technique. In the search for heavy Higgs bosons decaying to two W's it may also be necessary to identify jet pairs from W in order to ensure a statistically significant signal.[4]

The observed production of W and Z in proton-antiproton interactions at the predicted rates verified the standard-model coupling of W or Z to light quarks.[3] However, the direct observation of W or Z decay to quark jets is difficult at hadron colliders because of the large background of dijet events from hard parton-parton scattering. The UA2 experiment has reported an approximately 3-standard-deviation structure in the W or Z mass region (65–105 GeV/c^2) in the invariant-mass distribution of jet pairs.[5] The structure contains 632 ± 190 events compared to the standard-model prediction of 340 ± 80 events. The signal-to-background ratio is approximately 1/20.

The dominant source of dijets at $p_T \approx m_W/2$ is elastic scattering of gluons and light quarks which is approximately 2 orders of magnitude greater than the W decay signal.[6] On the other hand, if one considers heavy-quark ($Q = c, b$) channels the cross section for c/b production by W or Z decay are comparable to those of the lowest-order QCD processes at the same p_T (Ref. 6).

We report here on a search for the decays $W \to c\bar{s}$, $Z \to c\bar{c}, b\bar{b}$ in which c/b jets are tagged by the presence of a high-p_T muon in or close to the jet.[7] Recent UA1 studies indicate that such muon-in-jet events are predominantly due to semileptonic decays of c and b quarks.[8,9] As discussed below these events are free of gluon and light-quark background except for a subset in which the muons come from π/K decay in flight. The same UA1 studies have also confirmed QCD predictions that α_s^3 processes such as $gg \to gg$, $g \to c\bar{c}$ make a substantial contribution to strong $Q\bar{Q}$ production. Thus, the signal-to background ratio for W or Z decay to jets is not expected to be as favorable as it appeared in Ref. 6, in which only α_s^2 processes were considered.

This study was made with events recorded with an inclusive muon trigger in the UA1 detector at the CERN SPS proton-antiproton collider. The total integrated luminosity was 551 nb^{-1} at a center-of-mass energy of 630 GeV. The muon detector and triggering system have been described in detail elsewhere.[10] The work discussed here is based on a sample of 20 000 events having a reconstructed muon with $p_T > 6$ GeV/c. Details of event reconstruction are given elsewhere.[11]

The decay of W or Z to a quark-antiquark pair should appear as a pair of jets; for low-p_T boson production the jets collinear in the plane transverse to the beams. We require that one jet be accompanied by a muon, consistent with the semileptonic decay of a c or b hadron. The final selection consists of events with (i) a muon with $p_T > 8$ GeV/c accompanied by a jet within the cone $\Delta R(\mu\text{-jet}) < 1$ in pseudorapidity-ϕ space, $\Delta R \equiv (\Delta\eta^2 + \Delta\phi^2)^{1/2}$ (the choice of 8 GeV/c for the muon p_T threshold is discussed later), and (ii) a jet with $p_T > 10$ GeV/c recoiling from the muon, with $|\phi(\mu - \text{jet})| > 90°$. No p_T requirement was imposed on the jet in (i) beyond the minimum value of 2.5 GeV implicit in the UA1 jet algorithm. Both jets were required to have $|\eta| < 2.0$ and were also required to be more than 20° from vertical in the transverse plane in order to avoid the vertical cracks in the calorimetry. The total number of events satisfying these criteria is 1703.

The π/K decay-in-flight background in these events was estimated to vary from $\lesssim 100\%$ for $p_T(\mu) > 3$ GeV/c to 20% for $p_T(\mu) > 20$ GeV/c. For the muon p_T threshold of 8 GeV/c used in this analysis, the background was estimated to be $37.9 \pm 1.5^{+8}_{-12}\%$. Details of the background calculation are given elsewhere.[7,9]

From the measured values of $\sigma B(W\rightarrow e\nu)$ and $\sigma B(Z\rightarrow ee)$ (Ref. 3), the standard model predicts a total of 1070 $c\bar{s}$ and 343 $c\bar{c}$ and $b\bar{b}$ events for the integrated luminosity of 551 nb^{-1}. The ISAJET Monte Carlo program,[12] in conjunction with a detector simulation package, has been used to calculate the effect of selection criteria and triggering and reconstruction efficiency of these statistics. Table I (row 3) shows a reduction to 13.8 (W) and 23.5 (Z) by the requirement of decay to a muon with $p_T > 8$ GeV/c. The further reduction to 3.2 (W) and 5.6 (Z) comes mainly from a 30% efficiency for triggering on and reconstructing the muon events.

Figure 1 shows on a logarithm-linear plot the invariant mass of (jet-jet-μ-ν_T) for the selected events; a logarithm ordinate is used in order to show the corresponding reconstructed masses of Monte Carlo distributions for $W\rightarrow c\bar{s}$ and $Z\rightarrow c\bar{c},b\bar{b}$. The statistical error in the W or Z mass range of 60–90 GeV/c^2 is four times the predicted signal. The longitudinal momentum of the neutrino is omitted since it is not measured. The mass resolution is around 20%. The reconstructed W or Z masses are shifted downward from their input values by about 15%, predominantly due to systematic underestimation of jet energies by the UA1 jet reconstruction algorithm; this effect is well understood.[13]

The experimental distribution in Fig. 1 can be explained completely in terms of strong $c\bar{c}$ and $b\bar{b}$ production and the decay background. In Fig. 2 the histogram is the data after subtraction of the π/K background, and the smooth curve is the ISAJET prediction for strong $c\bar{c}$ and $b\bar{b}$ production normalized to the total number of events plotted. The ISAJET prediction is within a factor of 1.09 of the experimental data, whereas the uncertainty in integrated luminosity alone gives a 15% error in the experimental cross section. The correspondence between ISAJET predictions and the data is not surprising since the validity of these predictions for $c\bar{c}$ and $b\bar{b}$ production has already been verified in studies of inclusive dimuon and single-muon events in experiment UA1 (Refs. 8 and 9).

As described in Ref. 9 the ISAJET Monte Carlo program provides c/b cross sections for the lowest-order QCD processes and for the next-higher-order processes in which an initial- or final-state gluon evolves to $Q\bar{Q}$ ("flavor excitation" and "gluon splitting," respectively). The dashed line in Fig. 2 shows the lowest-order strong production processes $gg/q\bar{q}\rightarrow Q\bar{Q}$; the solid curve includes flavor excitation and gluon splitting. In the region of the W or Z mass the total strong cross section exceeds the α_s^2 cross section by a factor of 5. It is evident that higher-order strong processes overwhelm the expected W or Z signal.

In order to obtain a W or Z signal at the n-standard-deviation level it is necessary that $N(W/Z)/[N(Q\bar{Q})]^{1/2} > n$, where $N(Q\bar{Q})$ denotes the strongly produced background. For the UA1 detector this quantity, evaluated over the range $M(\text{jet-jet-}\mu\text{-}\nu_T)=60$–90 GeV/$c^2$, passes through a broad maximum 0f 0.33 centered at $p_T(\mu)=8$ GeV/c. Hence, the choice of 8 GeV/c as the threshold for muon transverse momentum in this study. In the absence of measurement error, the ratio $N(W/Z)/[N(Q\bar{Q})]^{1/2}$ would increase as this threshold was lowered.

We have not considered here the possible existence of $W\rightarrow t\bar{b}$ decay. A search for this decay is described in detail in a separate publication.[14] A Monte Carlo study shows that this experiment would be sensitive to the existence of a low-mass top quark. For a top mass of 30 GeV/c^2 the number of $W\rightarrow t\bar{b}$ events expected in our final sample is 18, double the combined yield predicted for W or $Z\rightarrow c/b$. The $W\rightarrow t\bar{b}$ decay dominates over $W\rightarrow c\bar{s}$ because both top and bottom quarks can decay semileptonically, and both have harder fragmentations than charm. Higher-mass top quarks are eliminated by the requirement that the muon be close to the jet, reflecting the relatively small Q value for the quark decay.

The method of restricting the search for hadronic decays of W and Z bosons to heavy-quark modes has the advantage that the large α_s^2 gluon-scattering background is absent. As seen here, however, the strong production of charm and b flavor alone contribute a considerable background.

The probability of observing W or Z decays to c and b quarks can be improved by some obvious measures. In a detector with a more compact muon detection system, such as the D0 detector planned for the Fermilab Tevatron collider,[15] the decay-in-flight muon background is reduced. The highly segmented U/TMP calorimeter currently under construction for the UA1 detector[16] will improve the jet-jet mass resolution, thus, increasing the signal-to-background ratio. And, with the planned calorimeter segmentation $\Delta\eta\times\Delta\phi=0.1\times6°$, it may also be possible to differentiate quark and gluon jets and

TABLE I. Evolution of the W and Z statistics from the Monte Carlo study. The number of events corresponds to an integrated luminosity of 551 nb^{-1}.

		$W\rightarrow c\bar{s}$	$Z\rightarrow c\bar{c}$	$Z\rightarrow b\bar{b}$
ISAJET	All events	1070	153	190
	Decay to muon	97.5	27.5	85.4
	$p_T(\mu) > 8$ GeV/c	13.8	4.6	18.9
ISAJET	$p_T(\mu) > 8$ GeV/c	3.9	1.2	5.7
Detector simulation	Other analysis cuts	3.2	1.0	4.5

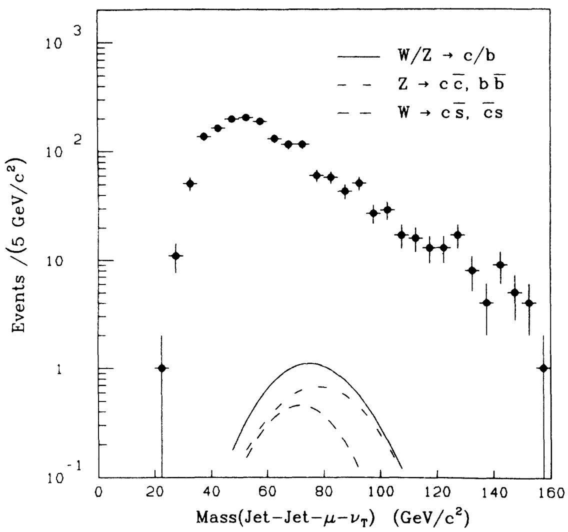

FIG. 1. Experimental distribution of the jet-jet-μ-ν_T mass without subtraction of the π/K decay background. The curves are the Monte Carlo predictions calculated with full simulation of the UA1 detector measurement errors for $W \rightarrow c\bar{s}$ (dashed), $Z \rightarrow c\bar{c}, b\bar{b}$ (dotted-dashed), and the sum of these two (solid curve).

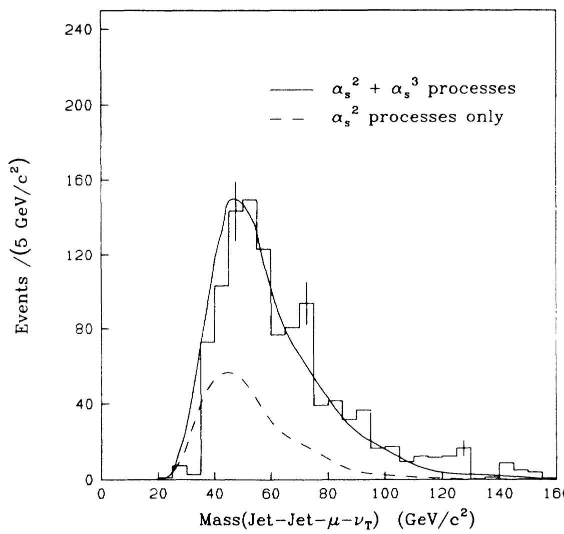

FIG. 2. Experimental distribution of the jet-jet-μ-ν_T mass, after subtraction of the background from π/K decay in flight. The smooth curve is the ISAJET prediction for strong $c\bar{c}$ and $b\bar{b}$ production, normalized (by a factor of 1.09) to the total number of events. The dashed curve is the prediction for lowest-order (2→2) strong production. The solid curve includes (2→3) processes.

hence, identify a fraction of the strong $Q\bar{Q}$ production background.

At the Tevatron ($\sqrt{s}=2$ TeV) it will be no easier to observe W or $Z \rightarrow b/c$ than at $\sqrt{s}$ of 630 GeV. For $\sqrt{s}$ of 2 TeV the ISAJET prediction is that strong c- and b-quark production will increase by an order of magnitude compared to a factor-of-3 rise for W and Z.

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