W PRODUCTION PROPERTIES AT THE CERN SPS COLLIDER

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ABSTRACT

The production properties of a sample of 172 charged Intermediate Vector Bosons produced at the CERN Super Proton Synchrotron Collider are described. The production cross-section, the longitudinal and transverse momentum distributions, and the properties of hadronic jet activity produced in association with the weak bosons are in agreement with the expectations of the QCD-improved Drell-Yan mechanism.

1. INTRODUCTION

Data taken at the CERN Super Proton Synchrotron (SPS) $p\bar{p}$ Collider during 1982 and 1983 have firmly established the existence of the charged ($W^\pm$) and neutral (Z^0) Intermediate Vector Bosons (IVBs) [1]–[5]. The production of W 's at the $p\bar{p}$ Collider proceeds by the Drell–Yan mechanism [6] in which a quark from the proton annihilates with an antiquark from the antiproton. In a quantum chromodynamics (QCD)-improved picture of the production mechanism the annihilating quark and antiquark are coloured, and there are higher-order corrections to the bare Drell–Yan process in which one or more gluons are radiated from the incoming partons. This initial-state gluon bremsstrahlung is expected to give rise to i) a long tail in the transverse momentum distribution of the weak bosons, and ii) the occasional observation of one or more hadronic jets produced in association with the higher transverse momentum IVBs. In the region in which QCD perturbation theory is applicable (for sufficiently large transverse momenta), the W transverse momentum distribution, together with the rate of occurrence and properties of hadronic jets produced in association with the W 's, provides us with a quantitative test of the theory.

During the 1982 and 1983 data-taking periods the Collider was operated at $\sqrt{s} = 546$ GeV, and from an integrated luminosity of 136 nb^{-1} the UA1 experiment [7] collected essentially background-free samples of 52 $W^\pm \rightarrow e^\pm \nu_e$ decays [1], 14 $W^\pm \rightarrow \mu^\pm \nu_\mu$ decays [2], 4 $Z^0 \rightarrow e^+e^-$ decays [3], and 5 $Z^0 \rightarrow \mu^+\mu^-$ decays [4]. Analysis of these event samples showed that the production properties of the $W^\pm$ and Z^0 are consistent with the expectations of the QCD-improved Drell–Yan mechanism, and the decay properties are consistent with the expectations of the $SU(2) \otimes U(1)$ Standard Model [8]. More recently, during the 1984 data-taking period, the Collider has been operated at the increased centre-of-mass energy of $\sqrt{s} = 630$ GeV and the UA1 Collaboration have recorded a further 263 nb^{-1} of data, tripling the size of the event samples, and enabling a more detailed examination of the production and decay properties of the $W^\pm$ and Z^0 to be made. The decay properties of the IVBs will be described in a forthcoming paper. In this paper we restrict ourselves to the W production properties, obtained from an analysis of 172 events in which a $W^\pm$ has been produced, subsequently decaying in the ($e^\pm \nu_e$) channel.

With these improved statistics it is shown that the QCD-improved Drell–Yan mechanism gives a good description of the event rates, and of the W longitudinal and transverse momentum distributions. The observation of hadronic jets produced in association with the weak bosons is firmly established, and the properties of these jets are shown to be in agreement with the expectations for jets arising from initial-state bremsstrahlung off the incoming annihilating partons. Finally, there is no evidence in the current data sample for the existence of a massive object X which subsequently decays into a $W^\pm$ and one or more hadronic jets.

The UA1 detector is a general-purpose apparatus designed to study, as systematically as possible, the phenomenology of $p\bar{p}$ collisions at the Collider. The apparatus and the data-taking conditions are essentially unchanged from those reported in our previous publications, and we refer the reader to Ref. [1] for more details. The main features of the UA1 detector and event reconstruction relevant to the present paper are the following.

- i) *Electron detection.* Energetic electrons deposit almost all their energy in the UA1 lead-scintillator electromagnetic shower calorimeter, 27 radiation lengths deep, and deposit very little energy in the hadron calorimeter beyond this. The energy resolution of the electromagnetic calorimeter is approximately $\Delta E_{\text{rms}} = 0.16 \sqrt{E}$, where all energies are in GeV.

- ii) *Neutrino detection.* The presence of neutrino emission is inferred from an apparent lack of momentum conservation in the two components transverse to the beam direction. The detection and measurement of neutrino emission by this method is made possible in the UA1 detector by the nearly complete solid-angle coverage of calorimeters down to 0.2° from the direction of the beams. The accuracy in each component of missing transverse energy is $0.4 \sqrt{E_T}$, where E_T is the scalar sum of the transverse energies deposited in all the calorimeter cells and all energies are in GeV.
- iii) *Momentum analysis and charged-particle determination.* This is performed with accurate curvature measurement by the central detector, a large-volume drift chamber surrounding the crossing point and operated in a homogeneous 0.7 T magnetic field. The central detector is also used to determine the charged-particle topology of the event and, in particular, the isolation criteria for the electron track.
- iv) *Jet finding and reconstruction.* The UA1 jet-finding algorithm has been described elsewhere [9]. A momentum vector is associated with each calorimeter cell. Its direction and magnitude are defined by the spatial position of the cell and the energy deposition within the cell. The cells with transverse energy in excess of 2.5 GeV are grouped in clusters and their associated momentum vectors are added if the distance between them in (pseudorapidity, azimuthal angle)-space ΔR is less than 1 [$\Delta R \equiv (\Delta\eta^2 + \Delta\phi^2)^{1/2}$, where ϕ is in radians]. Cells with lower transverse energy are then included in the cluster if they are within $\Delta R < 1$ with respect to the cluster axis. Jets are retained if they have a transverse momentum in excess of 5 GeV/c, and an axis within the pseudorapidity interval $|\eta| < 2.5$. A detailed study of the relationship between the four-momentum of jets reconstructed by this method and the four-momentum of the underlying parton has been made using ISAJET [10] with the fragmentation function of Field and Feynman [11]. The results of this study suggest that the jet energy is underestimated by about 20% and the jet momentum by about 15%. The implied scale shift, which is model-dependent, does not alter the essential results presented in this paper. For definiteness we do not correct the reconstructed jet four-momentum for this effect.

2. EVENT SAMPLE

Results are based on an integrated luminosity of 399 nb^{-1} , which is corrected for dead-time and other similar losses, and which includes the data samples from previous publications [1].

2.1 Event selection

The trigger used throughout the data taking required the presence of an electromagnetic cluster (one or two adjacent electromagnetic calorimeter cells) with a transverse energy in excess of 10 GeV, and at an angle of more than 5° with respect to the beam direction. After complete off-line reconstruction, about 5×10^5 events had at least one electromagnetic (e.m.) cluster with transverse energy $E_T > 15 \text{ GeV}$. To extract an essentially background-free sample of $W^\pm$ decays, the following cuts have been applied to the data:

- i) *Cluster validation.* To ensure that we have a reliable reconstruction for the e.m. cluster, we require that, after removing the central detector track with the highest transverse momentum (the electron candidate), the sum of the transverse momenta of all other tracks entering the two calorimeter cells associated with the cluster is less than 3 GeV/c. We further

require that the centroids of the energy depositions in the four longitudinal samplings of the e.m. calorimeter are consistent with a single e.m. cluster.

- ii) *Associated track requirement.* If the e.m. cluster is at an angle of more than 15° with respect to the horizontal, where the central detector has good efficiency, we require the presence of a charged track in the central detector associated with the cluster, and with transverse momentum consistent with being in excess of 15 GeV/c.
- iii) *Loose isolation.* To exclude two-jet events in which one jet fakes the electron signature, we demand that the electron is isolated in a cone in (pseudorapidity, azimuthal angle)-space with radius $\Delta R = 0.4$, where $\Delta R \equiv (\Delta\eta^2 + \Delta\phi^2)^{1/2}$ and ϕ is in radians. The isolation conditions within this cone are that: a) after removing the track with the highest transverse momentum, the sum of the transverse momenta of all other tracks in the cone is less than 10% of the e.m. cluster transverse energy; and b) the cluster transverse energy is at least 90% of the total transverse energy (e.m. calorimeter plus hadronic calorimeter) inside the cone.
- iv) *Tight isolation.* To obtain further rejection against two-jet events we require additional isolation inside a larger cone with radius $\Delta R = 0.7$. The isolation conditions within this cone are that a) after removing the track with the highest transverse momentum, the sum of the transverse momenta of all other tracks in the cone is less than 3 GeV/c; and b) the sum of the transverse energy depositions in the calorimeter, after excluding the e.m. cluster, is less than 3.2 GeV.
- v) *Electromagnetic shape.* To reject hadronic showers faking an electron signature we require that a) the energy E_{had} deposited in the hadron calorimeter cell immediately behind the e.m. cluster, is either less than 2% of the e.m. cluster energy or less than 0.6 GeV (1.5 GeV) for clusters with pseudorapidity $|\eta| < 1.5$ ($|\eta| > 1.5$). We further require that b) the quality parameter χ_R^2 is less than 60, where χ_R^2 measures the goodness of fit to the electron hypothesis; χ_R^2 has been developed from a study of electron test-beam data, making full use of the longitudinal profile of the shower measured in the four samplings of the electromagnetic calorimeter, and taking into account the electron energy and angle of incidence. The expected χ_R^2 distribution for isolated electrons coming from $W^\pm \rightarrow e^\pm \nu_e$ decays is shown in fig. 1c.
- vi) *Neutrino emission.* Finally, we require that the missing transverse energy in the event is in excess of 15 GeV after validation during which obvious instrumental problems are removed. If the electron cluster is within 15° of the vertical direction there must be no reconstructed jet in the event (with transverse energy in excess of 7.5 GeV in the calorimeters, or transverse momentum in excess of 5 GeV in the central detector) which is also going in the vertical direction (within 15°).

After these requirements have been imposed on the data, we are left with a sample of 173 events. One event has a very low electron-neutrino transverse mass, and a topology consistent with the hypothesis $W \rightarrow t\bar{b}$ [12] (or possibly $p\bar{p} \rightarrow t\bar{t} + X$) with a subsequent semileptonic decay of the t-quark. We exclude this event from our sample by requiring that the transverse mass of the electron-neutrino system is in excess of 20 GeV/c².

We are left with a sample of 172 events for further analysis, of which 59 events come from collisions at $\sqrt{s} = 546$ GeV and 113 events come from collisions at $\sqrt{s} = 630$ GeV.

2.2 Background estimate

After our selection the distributions showing the electron quality and isolation for the sample of 172 W candidates are consistent with expectations for an essentially background-free sample of isolated electrons (figs. 1a-d). We have estimated, in detail, the possible sources of background in our sample of $W^\pm \rightarrow e^\pm \nu_e$ decays.

- i) *Hadronic interactions.* Hadronic jets can fake an isolated electron signature a) if they fragment in such a way that one energetic charged pion overlaps with one or more neutral pions, or b) if they contain a genuine energetic electron arising from heavy-flavour decays which overlaps with one or more neutrals. In both these cases we would expect a two-jet topology with little or no missing transverse energy in the event. To estimate the background from these sources, we drop the last requirement imposed in the selection, namely the presence of a missing transverse energy $\Delta E_m > 15$ GeV, and examine the missing transverse energy for the enlarged sample. For those events with $\Delta E_m < 15$ GeV the ΔE_m distribution is well described by the experimental resolution in the measurement of this quantity (fig. 2), and furthermore almost all these events have a two-jet topology. Extrapolating the resolution curve in the region $\Delta E_m > 15$ GeV, we estimate a background in our $W^\pm \rightarrow e^\pm \nu_e$ sample of 3.4 ± 1.8 events at $\sqrt{s} = 546$ GeV and 1.9 ± 0.6 events at $\sqrt{s} = 630$ GeV. As a final check, each of the 172 W events has been visually inspected on an interactive graphics display. Only 7 events have a hadronic jet coplanar with the electron and the beams. We retain these events in the data sample since they are consistent with events in which the jet arises from initial-state bremsstrahlung off the incoming partons and is only accidentally back-to-back with the electron in the transverse plane.
- ii) $W \rightarrow \tau \nu_\tau$. We have evaluated this background using the ISAJET Monte Carlo [10] together with a full simulation of the UA1 detector. We estimate a background of 11.8 ± 0.6 events from this source, of which 2.7 events are associated with the decay $\tau \rightarrow \pi^\pm (\pi^0) \nu_\tau$ and 9.1 events are associated with the decay $\tau \rightarrow e \nu_e \nu_\tau$.
- iii) $W \rightarrow t \bar{b}$. We have evaluated this background using the ISAJET Monte Carlo, taking $m_t = 40$ GeV/c² [12]. We estimate a background of 1.5 events before applying the requirement that the transverse mass of the electron-neutrino system is greater than 20 GeV/c². After this cut has been applied, this background becomes negligible.
- iv) $t \bar{t}$ production. Evaluation of background from this source is made difficult by the lack of knowledge of the $t \bar{t}$ production cross-section. A preliminary prediction from the EUROJET Monte Carlo [13] gives a production cross-section of 1.4 nb for $m_t = 40$ GeV/c², and a transverse momentum cut on the t-quarks of $p_T^{(t)} > 3$ GeV/c. Passing the Monte Carlo generated events through the W selection procedure and taking 0.12 for the top quark semileptonic decay branching ratio $B(t \rightarrow b e \nu_e)$, we find that 1% of the generated $t \bar{t}$ events survive the W selection cuts. This leads us to an estimated background of 7 events in the $W^\pm \rightarrow e^\pm \nu_e$ sample. However, this estimate is sensitive to m_t , the $t \bar{t}$ production cross-section, and the semileptonic branching ratio for the top quark. Since these quantities are not well known we make no correction for background from $t \bar{t}$ production in the following analysis.

3. DETERMINATION OF THE PRODUCTION CROSS-SECTION

The integrated luminosity of the experiment is 136 nb^{-1} at $\sqrt{s} = 546 \text{ GeV}$ and 263 nb^{-1} at $\sqrt{s} = 630 \text{ GeV}$, known to about $\pm 15\%$ uncertainty. We have used two techniques to estimate the efficiency of our selection requirements: i) the ISAJET Monte Carlo [10] together with a full simulation of the UA1 detector, and ii) a randomized W-decay technique in which the 172 real W events are used, but the electron is replaced by a generated electron coming from a random (V - A) decay of the produced W. The two methods give consistent results, which are shown in table 1.

We find that the efficiency of our trigger and selection requirements is 0.69 ± 0.03 for the $\sqrt{s} = 546 \text{ GeV}$ data sample and 0.62 ± 0.03 for the $\sqrt{s} = 630 \text{ GeV}$ sample. The cross-section is then:

$$(\sigma \cdot B)_{\widetilde{W}} = 0.55 \pm 0.08 (\pm 0.09) \text{ nb}$$

at $\sqrt{s} = 546 \text{ GeV}$, where the last error takes into account the systematic errors. This cross-section is consistent with the previously published value of 0.53 nb [1]. The small change is due to an improved and extended selection, and to a more thorough evaluation of the selection efficiencies. Our result is in good agreement with the corresponding result from the UA2 experiment [5], $0.53 \pm 0.10 (\pm 0.10) \text{ nb}$, and is not far from the prediction of Altarelli et al. [14] of $0.38^{+0.12}_{-0.05} \text{ nb}$, where we take the branching ratio $B = 0.089$.

The corresponding experimental result for the 1984 data at $\sqrt{s} = 630 \text{ GeV}$ is

$$(\sigma \cdot B)_W = 0.63 \pm 0.05 (\pm 0.09) \text{ nb}.$$

This is in agreement with the theoretical expectation [14] of $0.47^{+0.14}_{-0.08} \text{ nb}$. We note that the 15% systematic uncertainty on these results disappears in the ratio of the two cross-sections. We obtain the result

$$\sigma_W(\sqrt{s} = 630 \text{ GeV}) / \sigma_W(\sqrt{s} = 546 \text{ GeV}) = 1.15 \pm 0.17,$$

in agreement with the theoretical expectation of 1.24.

4. LONGITUDINAL MOMENTUM

The longitudinal momentum distribution of the W boson is expected to reflect the structure functions of the incoming annihilating partons, predominantly u-quarks and d-quarks. Unfortunately we do not measure the longitudinal momentum of the W directly since we do not measure the longitudinal component of the neutrino momentum. We can overcome this difficulty by imposing the mass of the W on the electron-neutrino system. This will yield two solutions for the longitudinal component of the neutrino momentum, one corresponding to the neutrino being emitted forwards in the W rest frame, the other corresponding to the neutrino being emitted backwards. Hence we have two solutions for x_W , the Feynman x for the W. In practice, in one-third of the events one of these two solutions for x_W is trivially unphysical ($x_W > 1$), and in another one-third the ambiguity is resolved after consideration of energy and

momentum conservation in the whole event. In the cases where the ambiguity in x_W is resolved, it tends to be nearly always the lowest of the two x_W solutions which is chosen. In the following analysis the lowest of the two solutions will be used for all the events.

Taking $84 \text{ GeV}/c^2$ for the mass of the W , the resulting x_W distribution is shown in fig. 3a for the $\sqrt{s} = 546 \text{ GeV}$ and $\sqrt{s} = 630 \text{ GeV}$ data samples separately. There is some indication of the expected softening of the W longitudinal momentum distribution with increasing $\sqrt{s}$. The data are in reasonable agreement with the expectation resulting from the structure functions of Eichten et al. [15] with $\Lambda = 0.2 \text{ GeV}$. Using the well-known relations

$$x_p x_{\bar{p}} = m_W^2/s \quad (\text{energy conservation})$$

and

$$x_W = |x_p - x_{\bar{p}}| \quad (\text{momentum conservation}),$$

we can determine the parton distributions in the proton and antiproton sampled in W production. The results are shown in fig. 3b. The proton- and antiproton-parton distributions are consistent with each other, and are well described by the structure functions of Eichten et al. For those events in which the charge of the electron, and hence the W , is well determined, we can identify the proton (antiproton) parton with a u - ($\bar{d}$)-quark for a W^+ , or a d - ($\bar{u}$)-quark for a W^- . There are 118 events in which the charge of the electron track is determined to better than 2 standard deviations (from infinite momentum). The resulting u - and d -quark distributions for these events are shown in figs. 3c and 3d, respectively. Once again there is agreement with the predictions of Eichten et al.

5. TRANSVERSE MOMENTUM

The W transverse momentum $p_T^{(W)}$ is obtained by adding the electron and neutrino transverse momentum vectors. The resulting distribution for $p_T^{(W)}$ is shown in fig. 4. The distribution peaks at a value $p_T^{(W)} \sim 4 \text{ GeV}/c$ (primarily reflecting the experimental resolution of the measurement of the missing transverse energy in the event), and has a long tail extending to $p_T^{(W)} \sim 40 \text{ GeV}/c$. The electron isolation criteria that we have used in defining the $W^\pm \rightarrow e^\pm \nu_e$ event sample introduce a bias against the more active [highest $p_T^{(W)}$] events. We have studied this bias using the randomized W decay technique described in Section 3. The average loss of events due to the isolation criteria rises from 4% for the lowest $p_T^{(W)}$ events to about 14% for the highest $p_T^{(W)}$ events. The effect is therefore small, and we can safely neglect it. The shape of the measured W transverse momentum distribution is in reasonable agreement with the expectations of the QCD-improved Drell-Yan model. As an example of the QCD predictions in fig. 4, we show the curve from Altarelli et al. [14] using the structure functions of GHR [16] with $\Lambda = 0.4 \text{ GeV}$. This gives an excellent description of the data.

6. JET ACTIVITY

The QCD-improved Drell-Yan mechanism predicts that the highest transverse momentum W 's are produced in association with one or more gluons radiated off the incoming annihilating quarks. If these gluons are sufficiently energetic and are emitted at sufficiently large angle to the beam direction, they will be observed as hadronic jets balancing the transverse momentum of the W and recoiling against the W in the plane transverse to the beam direction. The UA1 jet algorithm has been used to search for jet activity produced in association with the weak bosons. Hadronic jets are indeed found in those events containing the highest transverse momentum W 's (fig. 4). For events with $p_T^{(W)} > 20$ GeV/c, every event has at least one reconstructed jet. Furthermore, within the experimental resolution, the jet activity observed in W events does indeed balance $p_T^{(W)}$ (fig. 5). The resolution curve shown in fig. 5 is roughly a Gaussian with a width of $\sim 0.25 p_T^{(W)}$; it has been obtained using the ISAJET Monte Carlo together with a full simulation of the UA1 detector. A detailed study of the properties of the jets reconstructed in W events shows that they are fully consistent with the expected properties of jets arising from initial-state gluon bremsstrahlung.

6.1 Rate of jet activity

In 38% of the W sample, one or more hadronic jets with transverse momentum $p_T^{(j)}$ in excess of 5 GeV/c are observed. The number of observed events (table 2) decreases with increasing jet multiplicity by a factor of roughly 0.3 per additional jet. Defining $R^{(W)}$ [17],

$$R^{(W)} \equiv \sigma[W + \text{jet(s)}]/\sigma(W),$$

where $\sigma(W)$ is the cross-section for producing a W with no observed jets, we find $R_W = 0.61 \pm 0.10$. A similar preliminary analysis for Z^0 events gives $R_Z = 0.7 \pm 0.3$, and the ratio of these ratios $R \equiv R_Z/R_W = 1.1 \pm 0.5$. Clearly the rate of jet activity observed in Z^0 events is consistent with the rate observed in W events. Before we can compare the observed rate of jet activity with the expectations from perturbative QCD, we need to know the experimental efficiency for reconstructing low transverse momentum jets. Using the ISAJET Monte Carlo and the full simulation of the UA1 detector, we find that within the geometrical acceptance of the detector the reconstruction efficiency rises from zero at $p_T^{(j)} = 0$ to 20% at $p_T^{(j)} = 7$ GeV/c, 80% at $p_T^{(j)} = 13$ GeV/c and is 100% for $p_T^{(j)} \geq 20$ GeV/c.

To make a quantitative comparison with the predictions of perturbative QCD, we restrict ourselves to the region in which the reconstruction efficiency for jets within the acceptance of the detector is 100%, namely $p_T^{(j)} > 20$ GeV/c. At $\sqrt{s} = 546$ GeV we have one event with one jet passing this cut. After correcting the jet reconstruction efficiency for the geometrical acceptance of the detector (0.9) the resulting cross-section is $0.012^{+0.014}_{-0.007} (\pm 0.002)$ nb, in agreement with the QCD prediction of 0.010 ± 0.001 nb. This prediction is essentially that of ref. [17] recalculated to take into account the cuts used in defining the present UA1 $W^* \rightarrow e^+ \nu_e$ sample. At $\sqrt{s} = 630$ GeV we have six events with one jet with $p_T^{(j)} > 20$ GeV/c, corresponding to a cross-section of $0.041 \pm 0.015 (\pm 0.006)$ nb, once again in agreement with the QCD prediction of 0.016 ± 0.002 nb.

6.2 Jet kinematics

The jet transverse momentum distribution is shown in fig. 6. This distribution essentially reflects the $p_T^{(W)}$ distribution and is well described by the expectation from QCD perturbation theory for jets arising from initial-state bremsstrahlung. Furthermore, as expected, the angular distribution of these jets is strongly peaked in the beam directions. This can be seen in fig. 7 where the distribution of $\cos \theta^*$ is shown, θ^* being the angle between the jet and the average beam direction in the rest frame of the W and the jet(s). In the region in which the experimental acceptance is reasonably constant ($|\cos \theta^*| < 0.95$) the shape of the angular distribution is well described by the QCD expectation for bremsstrahlung jets, which is basically $(1 - |\cos \theta^*|)^{-1}$. Finally, we examine the invariant mass of the (W + 1 jet)-system for those events in which one jet has been reconstructed by the UA1 jet algorithm (fig. 8). The shape of this mass distribution is a little broader than the expectation from ISAJET. It is, however, well described by a simple Monte Carlo in which the observed W four-vectors are randomly associated with the four vectors from our sample of jets, suggesting that the shape of the (W + 1 jet) mass plot is controlled more by the proton structure functions than by the QCD matrix element.

We conclude from this mass distribution that there is no evidence for the production of a massive-state X which subsequently decays into a W plus one jet. For a mass $m_X > 180 \text{ GeV}/c^2$, with X subsequently decaying into a W and a single hadronic jet, we place an upper limit on the production cross-section for X of

$$\sigma \cdot B_{(X \rightarrow W + \text{jet})} / \sigma_W < 0.013$$

at 90% confidence level.

7. SUMMARY AND CONCLUSIONS

The properties of W bosons production at the CERN SPS $p\bar{p}$ Collider are in agreement with the expectations for W's produced by the QCD-improved Drell-Yan mechanism. The longitudinal motion of the W's reflects the longitudinal momentum distributions of the incoming partons, and is well described by the structure functions of Eichten et al. The transverse motion of the W's shows a long tail in the $p_T^{(W)}$ distribution, reflecting the importance of QCD radiative corrections to the bare Drell-Yan process. The transverse momentum distribution is well described by the QCD prediction of Altarelli et al. Furthermore, hadronic jets are observed, produced in association with the higher transverse momentum bosons. These jets exhibit the expected properties for jets arising from initial-state bremsstrahlung off the incoming partons, and occur at a rate which is consistent with the predictions of QCD perturbation theory. Finally, the overall production cross-section for W production at the Collider is in agreement with current theoretical expectations.

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REFERENCES AND FOOTNOTES

- [1] G. Arnison et al. (UA1 Collaboration), Phys. Lett. **122B** (1983) 103; **129B** (1983) 273.
- [2] G. Arnison et al. (UA1 Collaboration), Phys. Lett. **134B** (1984) 469.
- [3] G. Arnison et al. (UA1 Collaboration), Phys. Lett. **126B** (1983) 398.
- [4] G. Arnison et al. (UA1 Collaboration), Phys. Lett. **147B** (1984) 241.
- [5] M. Banner et al. (UA2 Collaboration), Phys. Lett. **122B** (1983) 476.
P. Bagnaia et al. (UA2 Collaboration), Phys. Lett. **129B** (1983) 130; Z. Phys. C: Particles and Fields **24** (1984) 1.
- [6] S. Drell and T.M. Yan, Phys. Rev. **25** (1970) 316, and Ann. Phys. **66** (1971) 578.
- [7] UA1 Proposal, A 4π solid-angle detector for the SPS used as a proton-antiproton collider at a centre-of-mass energy of 540 GeV, CERN/SPSC 78-06 (1978).
- [8] S. Weinberg, Phys. Rev. Lett. **19** (1967) 1264.
A. Salam, Proc. 8th Nobel Symp., Aspenäsgråden, 1968 (Almqvist and Wiksell, Stockholm, 1968), p. 367.
- [9] G. Arnison et al. (UA1 Collaboration), Phys. Lett. **123B** (1983) 115.
- [10] F.E. Paige and S.D. Protopopescu, ISAJET program, BNL 29777 (1981).
- [11] R.D. Field and R.P. Feynman, Nucl. Phys. **B136** (1978) 1.
- [12] G. Arnison et al. (UA1 Collaboration), Phys. Lett. **147B** (1984) 493.
- [13] The EUROJET Monte Carlo program contains all first-order (α_s^2) and second-order (α_s^3) QCD processes [see B. van Eijk, UA1 Technical Note UA1/TN/84-93 (1984), unpublished, and A. Ali, E. Pietarinen and B. van Eijk, to be published]. The heavy quark is fragmented using the parametrization of C. Peterson et al., Phys. Rev. **D27** (1983) 105 and the V-A decay matrix elements.
- [14] G. Altarelli, R.K. Ellis, M. Greco and G. Martinelli, Nucl. Phys. **B246** (1984) 12.
G. Altarelli, R.K. Ellis and G. Martinelli, Altarelli et al. Z. Phys. C: Particles and Fields **27** (1985) 617.
- [15] E. Eichten et al., Rev. Mod. Phys. **56** (1984) 579.
- [16] M. Glück, E. Hoffmann and E. Reya, Z. Phys. **C13** (1982) 119.
- [17] S. Geer and W.J. Stirling, Phys. Lett. **152B** (1985) 373.

Table 1

Selection efficiency. The efficiency for each cut in the selection leading to the sample of $172 W^\pm \rightarrow e^\pm \nu_e$ events is shown, evaluated by the two methods described in the text. The efficiency given for each requirement is for those events passing all preceding requirements.

Cut	Efficiency			
	$\sqrt{s} = 546 \text{ GeV}$		$\sqrt{s} = 630 \text{ GeV}$	
	Events with random decay	ISAJET	Events with random decay	ISAJET
Electron $E_T > 15 \text{ GeV}$	0.86	0.87	0.85	0.84
i) Cluster validation	0.97	0.96	0.96	0.95
ii) Associated track requirement	0.97	0.98	0.95	0.99
iii) Loose isolation (in cone $\Delta R = 0.4$)	0.98	0.99	0.98	0.98
iv) Tight isolation (in cone $\Delta R = 0.7$)	0.98	0.98	0.93	0.98
v) Electromagnetic shape:				
a) hadronic energy	0.95	0.95	0.95	0.95
b) χ^2_R	0.99	0.98	0.99	0.99
vi) Neutrino emission	0.98	0.97	0.97	0.96
Trigger efficiency	0.96	0.96	0.96	0.96
Overall efficiency	0.69 ± 0.03	0.68 ± 0.03	0.62 ± 0.03	0.66 ± 0.03

Table 2

Rate of occurrence of jets in W events

$\sqrt{s}$ (GeV)	Number of events						Total number of jets
	Total	≥ 1 jet	1 jet	2 jet	3 jet	4 jet	
546	59	17	15	1	1	0	20
630	113	48	35	7	4	2	69
TOTAL	172	65	50	8	5	2	89

Figure captions

Fig. 1 Electron quality and isolation.

- a) The sum of the transverse energy depositions in the calorimeters in a cone of $\Delta R = 0.7$ around the electron, after excluding the electron cluster.
- b) The sum of the transverse momenta of charged tracks in the central detector in a cone of $\Delta R = 0.7$ around the electron, after excluding the electron track.
- c) χ^2_R , a measure of the goodness of fit of the longitudinal shower profile to the electron hypothesis.
- d) The energy deposition in the hadron calorimeter cells immediately behind the electron cluster.

The curves are Monte Carlo predictions for electrons coming from $W^+ \rightarrow e^+ \nu_e$ decays.

Fig. 2 Background from two-jet fluctuations. The missing transverse-energy squared ΔE_m^2 divided by the experimental resolution on this quantity is shown for the sample of 1287 events which come from the W selection procedure (applied to the $\sqrt{s} = 630$ GeV data) after removing the requirement that $\Delta E_m > 15$ GeV. The contribution from the 113 W events (hatched sub-histogram) agrees well with the ISAJET prediction. The contribution from the other events having $\Delta E_m < 15$ GeV (non-hatched) is well described by the experimental resolution (dashed) curve. Extrapolating this curve under the W region we expect a background of 1.9 ± 0.6 events from jet-jet fluctuations.

Fig. 3 Longitudinal momentum distributions.

- a) Feynman x-distribution for W's produced in $p\bar{p}$ collisions at $\sqrt{s} = 546$ GeV (open circles) and $\sqrt{s} = 630$ GeV (full circles). The curves show the predictions using the structure functions of Eichten et al. [15] modified in the appropriate way to take into account selection biases, experimental resolution, and the analysis bias of choosing always the low x_W solution (see text).
- b) Feynman x-distributions for the proton and antiproton partons making the W. The curve shows the Eichten et al. prediction.
- c) Feynman x-distribution for u-quarks sampled in W production. The curve shows the Eichten et al. prediction.
- d) Feynman x-distribution for d-quarks sampled in W production. The curve shows the Eichten et al. prediction.

Fig. 4 The W transverse momentum distribution. The curve shows the QCD prediction of Altarelli et al. [14]. The hatched sub-histogram shows the contribution from events in which the UA1 jet algorithm reconstructs one or more hadronic jets with transverse momentum in excess of 5 GeV/c, in the rapidity interval $|\eta| < 2.5$.

Fig. 5 W-jet transverse momentum balance. The imbalance between the W and jet transverse momenta is shown as a fraction of the W transverse momentum for those events with $p_T^{(W)} > 5$ GeV/c. The curve is the prediction using the ISAJET program for the expected experimental resolution on this quantity.

Fig. 6 Jet transverse momentum distributions for all jets produced in association with the W. The curve shows the QCD prediction of ref. 17 normalized to the tail of the distribution (the region in which we expect to have good reconstruction efficiency for the jets).

- Fig. 7** The angular distribution for jets reconstructed in W events. The distribution of $\cos \theta^*$ is shown, θ^* being the angle between the jet and the average beam direction in the rest frame of the W and the jet(s). The curve shows the QCD prediction from ref. 17.
- Fig. 8** The (W + jet)-mass distribution for events in which one jet is reconstructed by the UA1 jet algorithm. The curves show the predictions of ISAJET (dashed curve) and event mixing (solid curve) in which W four-vectors and jet four-vectors from jets in W events are randomly associated.

Fig. 1 a)

Fig. 1 b)

Fig. 1 d)

Fig. 1 c)

Fig. 2

Fig. 3 a)

Fig. 3 b)

Fig. 3 c)

Fig. 3 d)

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8