Production of W's with Large Transverse Momentum at the CERN Proton-Antiproton Collider.

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ABSTRACT

We have measured the W transverse momentum distribution (p_T^W) using a sample of 323 $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ events produced in proton-antiproton collisions at the CERN collider. In the present letter we extend the study of the distribution up to $p_T^W \approx m_W$ and compare to leading and higher order QCD. This comparison is a precise test of QCD with hadron colliders and the inclusive spectrum gives good agreement over a large range of p_T^W . However we observe two events at very large p_T^W (≈ 100 GeV/c) in which the W candidate recoils against an energetic di-jet system. Both events have a very large missing transverse energy and a jet-jet mass compatible with the W mass. In a separate analysis, a topologically similar event has been observed in which a high mass di-jet system is balanced by a large missing transverse energy which could be interpreted as a $Z^0 \rightarrow \bar{\nu}\nu$ decay. We cannot easily explain these three events in terms of explicit second-order QCD calculations. However we cannot exclude at this stage the possibility that they are the result of non-gaussian fluctuations in the response of UA1 calorimetry or a statistical fluctuation in the data.

1.—Introduction. The production of charged Intermediate Vector bosons (W's) at the CERN proton-antiproton Collider proceeds predominantly by the Drell-Yan mechanism[1] in which a quark annihilates with an antiquark. In the QCD picture of the production mechanism there are higher order corrections in which one or more gluons are radiated from the incoming partons. This initial state bremsstrahlung is expected to give rise to a long tail in the W transverse momentum distribution and the higher transverse momentum W's are expected to be produced in association with one or more hadronic jets. This has been confirmed experimentally in a previous publication[2]. In the region in which QCD perturbation theory is applicable (for sufficiently large transverse momenta), the W transverse momentum distribution, together with the properties of the associated hadronic jets provides us with a quantitative test of the theory. This channel is of interest because of its simplicity and precision with respect to other purely hadronic channels : an excess of large transverse momentum W's , or a deviation of the properties of the associated jets from those expected, may signal the emergence of a new phenomenon.

2.—Event Selection and Reconstruction. In this paper we present the results from an analysis of the W transverse momentum distribution based on a sample of 266 $W \rightarrow e\nu$ decays and 57 $W \rightarrow \mu\nu$ decays. These data samples were accumulated during the period 1982 - 1985 at centre-of-mass energies $\sqrt{s} = 546$ GeV (136 nb⁻¹ for $W \rightarrow e\nu$ decays) and 630 GeV (568 nb⁻¹ for $W \rightarrow e\nu$ decays and 559 nb⁻¹ for $W \rightarrow \mu\nu$ decays). We refer the reader to previous publications[3] for details of the UA1 detector, and the cuts used to select our $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ event samples. Here we briefly summarise the main selection requirements and details of the reconstruction of hadronic jets:

i) *W $\rightarrow e\nu$ selection.* The trigger selected events containing an electromagnetic cluster with uncorrected transverse energy $E_T > 10$ GeV. After off-line reconstruction we require a cluster with $E_T > 15$ GeV matching with a central detector track with transverse momentum $p_T > 7$ GeV/c. The cluster must also be isolated within a cone of radius $\Delta R = (\Delta\eta^2 + \Delta\phi^2)^{1/2} < 0.4$, where η is the pseudo-rapidity and ϕ is the azimuthal angle measured in radians. The summed p_T (E_T) from extra tracks within the cone must each be less than 10% of the cluster E_T and less than 3.0 GeV/c (3.2 GeV). The cluster shape should be consistent with the expected shape for an isolated

electromagnetic shower. Finally, the missing transverse energy in the fully reconstructed event must be > 15 GeV. This selection results in a sample of 266 $W \rightarrow e\nu$ candidates.

ii) *$W \rightarrow \mu\nu$ selection.* The trigger selected events with a track in the UA1 muon chambers which points to the interaction vertex within 150 mrad. After off-line reconstruction a good quality matching track is required in the central detector with $p_T > 15$ GeV/c. This track must be isolated within a cone of radius $\Delta R < 0.4$, with the summed E_T of calorimeter cells (excluding the expected muon deposition) < 3 GeV, and the summed p_T of extra tracks < 1 GeV/c. There must be no jet with $E_T > 10$ GeV in a larger cone of radius $\Delta R = 0.7$ around the muon in either the calorimeters or the central detector and no jet with $E_T > 10$ GeV (7.5 GeV) in the calorimeters (central detector) within $\pm 30^\circ$ of being antiparallel to the muon in the transverse plane. Finally the missing transverse energy in the event must be > 15 GeV. After applying technical cuts to remove muons from π/K decays or cosmic rays, and validation of the muon quality by a physicist on a high resolution graphics display, we are left with a sample of 57 $W \rightarrow \mu\nu$ candidates.

iii) *Jet reconstruction.* Hadronic jets are identified by the standard UA1 jet-finding algorithm with a transverse energy initiator of 2.5 GeV, and have been retained if they have a transverse momentum in excess of 7 GeV/c, and an axis within the pseudorapidity interval $|\eta| < 2.5$ [2,4]. A detailed comparison has been made between reconstructed jets and the corresponding partons using the ISAJET Monte Carlo program[5]. On average, for jets with large transverse momentum ($P_T^J \geq 20$ GeV/c), the jet energy is underestimated by about 20% and the jet momentum by about 15%. The main contribution to these factors comes from the smaller response of the electromagnetic calorimeters to charged hadrons compared to electromagnetic particles, as measured in test beams and implemented in our simulation[6]. For lower transverse momenta the relationship between the observed and underlying jet energies is less certain, depending critically on the details of jet fragmentation and the contribution to the jet energy from the spectator event. We have corrected all the reconstructed jets for these effects, using average correction factors which are functions of the jet P_T , η and ϕ . We estimate that the remaining systematic uncertainty on the jet energy scale is $\approx 9\%$ [7].

3.—Comparison of Inclusive W Production with QCD. In Fig 1(a) we plot the quantity $1/N \frac{1}{p_T^W} \frac{dN}{dp_T^W}$ as a function of p_T^W for our sample of 323 leptonic decays. The distribution has been corrected for detection and selection inefficiencies and for the effects of detector resolution so that it can be compared directly with theoretical predictions[8,9]. The correction factors to the number of events, taking into account all effects have been determined to a precision $\approx 10\text{-}15\%$. These vary as a function of p_T^W from ≈ 2 at low p_T^W (5 GeV/c) to ≈ 4 at very large p_T^W (100 GeV/c) for the electron channel, and are roughly a factor of four larger for the muon channel. We estimate that the resolution on p_T^W is $\approx 15\%$ of the p_T for large values of p_T^W and that the systematic error on the energy scale is $\approx 9\%$.

The curves show the predictions for QCD processes. The solid curve shown up to $p_T^W \approx 25$ GeV/c has been calculated to all orders using the soft gluon resummation technique of Ref [9] and the structure functions of Duke and Owens with $\Lambda_{\text{QCD}} = 0.2$ GeV (DO1) and $\alpha_s = \alpha_s(m_W^2)$. Above 25 GeV/c no full QCD calculation is currently available. The shaded band shown between 25 and 60 GeV/c results from a perturbative calculation to order α_s , normalised by the lowest order W cross-section. As discussed in Ref. [9], it is expected that this quantity is relatively independent of higher order corrections. The theoretical uncertainty indicated by the width of the band is the result of the combined uncertainties from the choice of Q^2 -scale used for α_s and the choice of parton distributions. Above 60 GeV/c the calculations have been extrapolated using a version of ISAJET which has been tuned to reproduce the large p_T^W rates of Ref. [9] in the region $25 < p_T^W < 60$ GeV/c. The data extend up to values of $p_T^W \approx 100$ GeV/c. Below 25 GeV/c the agreement between the data and the full QCD calculation is very good. At larger values of p_T the data tend to stay systematically above the theoretical predictions.

In order to look in more detail at the very large p_T region we have transformed the differential spectrum into an integral one. Fig. 1(b) shows the observed fraction, R , of W events with $p_T^W > p_T^0$ as a function of the threshold value p_T^0 . The data is shown as a histogram to which no corrections have been made for acceptance and resolution. These corrections approximately cancel each other leaving small corrections $\approx 10\%$ which have been applied to the theoretical predictions discussed above. For $p_T^W > 40$ GeV/c we observe 6 events in good agreement with the predicted 4.2 ± 1.2 events. In the measured spectrum there is a large gap which extends from ≈ 50 GeV/c

to ≈ 80 GeV/c, followed by two events (A and B) which have been combined to give the last bin at $p_T^W \approx 90$ GeV/c in Fig. 1(a). The predicted number of events is 1.0 ± 0.3 for $p_T^W > 60$ GeV/c and 0.20 ± 0.06 for $p_T^W > 80$ GeV/c. Therefore, neglecting the detailed topology of the jet final states at high p_T^W , the rate of events is statistically compatible with QCD predictions. This is examined in more detail in the following sections.

4.—Analysis of $W + 2$ Jet Events. There is a striking similarity between the topologies and kinematics of events A (Fig 2a) and B (Fig 2b). Both events contain a W^+ candidate recoiling against an energetic di-jet system. In event A(B) the W decays leptonically into a muon(electron) - neutrino system in which the neutrino (missing transverse energy) carries a very large fraction of the transverse momentum of the W . The di-jet system is similarly asymmetric in its transverse energies, with one jet ≈ 80 GeV and the second ≈ 20 GeV. In both events, the jets are well measured by the detector and have electromagnetic/hadronic and charged/neutral energy ratios which are typical of jets of these energies. We also note that the jet-jet mass is $\approx m_W$ for both events and that the W -jet-jet mass is consistent with a common mass ≈ 290 GeV/c². A summary of the measured and computed parameters of the events is given in Table 1.

In order to compare with events of similar topology, we have selected the sample of leptonic W decays in which two hadronic jets are reconstructed, each with $P_T > 7$ GeV. There are ten such W -jet-jet events (3 muon and 7 electron), including events A and B. They can be characterised by 3 variables which are not independent: the transverse momentum of the W (p_T^W), the mass of the jet-jet system (m_{jj}) and the mass of the W -jet-jet system (m_{Wjj}). In Figs. 3 to 5 we show the correlations of these quantities and compare the data with the expectations of second order QCD.

5.—Comparison with 2nd Order QCD. The QCD calculation has been done with the second order W -jet-jet Monte Carlo program of Ref. [10]. This program does not fragment the outgoing partons and therefore generated events cannot be transported through the full detector simulation. However we have included in the calculation a simple simulation of the detector geometrical acceptance and selection losses, taking account of the effects of detector resolution on the charged lepton, jets and missing transverse energy. The resulting calculation predicts 8.4

W-jet-jet events in our data. There is an error on this prediction of at least a factor two due to the intrinsic uncertainty of the second order calculation, and also to the uncertainty at low p_T on the relationship between the parton energy and the observed jet energy. An independent estimate of this prediction has been obtained using ISAJET which includes a fragmentation model for partons and beam jets, tuned to our data, and also incorporates multi-gluon radiation from initial and final partons. This gives a prediction of 10 W-jet-jet events after detector simulation and selection. We conclude that the observed and predicted rates are in rather good agreement.

The contours in Figs. 3 to 5 are the second order QCD predictions, smeared by the jet resolution, for equal event density, containing respectively 68%, 95% and 99% of the expected events. The experimental distribution of the 8 observed events with $p_T^W < 30$ GeV/c is consistent with that expected from second order QCD. By contrast events A and B lie in a region of very low probability. In the region $p_T^W > 80$ GeV/c and $M_{Wjj} > 250$ GeV/c², which includes both events and for which the second order calculation is reliable and less affected by jet definition problems, the expected number of events is 0.04 ± 0.02 . In an extended region of $p_T^W > 60$ GeV/c and $M_{Wjj} > 225$ GeV/c² the expected number of events is about four times larger. The quoted errors are the statistical errors on the Monte Carlo calculations. Experimentally the 9% energy scale uncertainty could change the quoted rates by a factor of 1.6. According to Ref [10] there are theoretical uncertainties related to higher order corrections, especially when specific jet topologies are considered. The second order calculation implies that a large fraction of W's with $p_T^W > 80$ GeV/c is produced with two jets; in particular the ratio (W+2 jet) / (W+1 jet) is estimated to exceed one in this region. Similarly, in this p_T range, ISAJET predicts jet multiplicities of: 39% 1 jet, 39% 2 jets and 22% >2 jets.

6.—Lepton Mis-identification Backgrounds. Another common feature of events A and B is that the charged lepton is not perfectly isolated. In event A there is one close track of $p_T=1.9$ GeV/c ($\Delta R=0.41$) and in event B there are two close tracks of $p_T=1.2$ GeV/c ($\Delta R=0.14$) and 0.7 GeV/c ($\Delta R=0.58$) respectively. We now consider possible backgrounds of hadronic origin, consistent with these observations, which could fake the charged lepton of event A or B. We note that the events would nevertheless remain difficult to explain because of the large missing

transverse energy.

Event A could in principle result from an unidentified π/K decay into a muon. Taking account of the two jet topology and the large missing transverse energy, we estimate the background from this source to be $< 10^{-4}$ events. For event B the electron plus two close tracks could arise from fluctuation of a jet such that it satisfies the electron quality cuts. We note also that the electromagnetic profile is not perfect and lies at the boundary of the selection cut. This background has been studied by looking for 3 jet events with large missing energy which satisfy the necessary topological cuts. Combining the result with our e/jet rejection factor of $< 10^{-4}$ we obtain a background estimate for event B of $< 10^{-3}$ events.

An alternative interpretation for event B could be a $W^+ \rightarrow \tau^+ \nu_\tau$ decay in which the W recoils against two high p_T jets and the τ decays hadronically into $\pi^+ + n\pi^0 + \bar{\nu}_\tau$ or leptonically into $e^+ \nu_e \bar{\nu}_\tau$. In support of this hypothesis we recall that the electron isolation is not perfect. In addition we note that, although the transverse energy of the electron reconstructed in the calorimetry is 19 ± 1 GeV, the momentum of the matching central detector track is only 9 ± 1 GeV/c. Using ISAJET, we have estimated the contribution from $W \rightarrow \tau \nu$ decays to be 0.01 ± 0.01 events. Similarly the expected contribution from $Z^0 \rightarrow \tau^+ \tau^-$ decays is 0.003 ± 0.003 events.

7.—Alternative Interpretations. We have considered other standard processes which may produce an isolated energetic charged lepton together with a very large missing transverse energy and two energetic hadronic jets such that $P_T^{lv} > 80$ GeV/c and $M_{lvjj} > 250$ GeV/c².

i) *Double parton scattering* with separate production of a W and two jets. This process is not expected to produce large p_T W's and the predicted contribution is negligible.

ii) *Heavy flavour production* ($b\bar{b}$, $c\bar{c}$, $t\bar{t}$) and *semileptonic decay*. The production of $t\bar{t}$ (or a new generation down-type quark with a mass below the top mass) is of particular interest since the production rate for events similar to A and B is a maximum when m_t is just above the W mass. In this case the t can decay into a real W and a b quark almost at rest. For $m_t \sim 90$ GeV/c² the expected number of events is 0.02 (+0.02,-0.01), where the main contribution to the error comes from the theoretical uncertainty on the lowest order QCD calculation. By comparison, for $40 \leq m_t \leq 60$ GeV/c² [11], we expect $\leq 4 \times 10^{-3}$ events. In obtaining these results we have

taken a K-factor of two, and considered both the muon and electron channels

iii) *Standard WW, WZ, or WH production.* In both events A and B the mass of the jet-jet system is within two standard deviations of the W mass. It is therefore natural to consider the possibility that the two jets arise from production of a second weak boson, either a W, a Z, or a Higgs boson (with $m_H \approx m_W$). Following ref. [12], and allowing for the W decay branching ratio B, we find $\sigma^{WW} \cdot B = 0.02$ pb.

A summary of these standard processes is given in Table 2. We conclude that none of them gives a likely explanation for events A and B. Other high P_T^W events have been reported by the UA2 collaboration[13]. However these events have rather different properties to events A and B and can be interpreted in terms of QCD production.

At the statistical level of two events in 323 we cannot exclude the possibility of a rare non-gaussian fluctuation of the response of the calorimetry. However the events have been carefully examined on interactive displays and there is no evidence for any abnormal behaviour of the detector.

We have also looked for the production of Z^0 's with large transverse momentum. In the e^+e^- and $\mu^+\mu^-$ channels, the observed P_T^Z distributions are entirely consistent with QCD expectations. However, in the missing E_T analysis[14], we have observed two events which could be interpreted as $Z^0 \rightarrow \bar{\nu}\nu$ decays at very large transverse momentum and which have similar topologies to those of events A and B. Both events have a very large missing transverse energy recoiling against an energetic di-jet system, but only one of them has a large jet-jet mass. We note that the minimal Z^0 -jet-jet mass of this event is ≈ 290 GeV/c², similar to events A and B, but that the jet-jet mass is larger than m_W (148 GeV/c²). Like events A and B, this event (C) is difficult to explain in terms of QCD. In the region $p_T^Z > 80$ GeV/c and $M_{Zjj} > 250$ GeV/c², where this event lies, we predict only 0.03 ± 0.03 events from known physics processes. The parameters of event C are given in Table 3 and the event is shown in Fig. 6.

8.—Conclusions. We have measured the W transverse momentum distribution out to very large values of P_T^W and find that inclusively the QCD predictions of the Drell-Yan mechanism give an acceptable description of the data over the observed range of P_T^W , once the relatively large

statistical errors are taken into account.

We have observed two events at very large $P_T^W (\approx 100 \text{ GeV}/c)$ in which the W-candidate recoils against a high mass , energetic di-jet system. As this is not a trivially expected topology for this region we have selected other W-jet-jet events and compared their properties with explicit second order QCD calculations. Of the ten events found we find that the rate and kinematical properties of the eight lower P_T^W events are well described by QCD. However the same calculation gives only a small probability for the observation of the two largest P_T^W events.

In a separate analysis a topologically similar event has been observed in which a high mass di-jet system is balanced by a large missing transverse energy. A possible interpretation of this event is a $Z^0 \rightarrow \bar{\nu}\nu$ decay at very large P_T^Z recoiling against two QCD jets. As with the two W events the corresponding QCD calculations give a low probability for the observation of such an event.

We have considered other standard processes which may produce events containing large P_T W or Z candidates and two energetic jets. Within the current theoretical framework of perturbative QCD we conclude that it is difficult to explain the three observed events. At this stage we cannot exclude unforeseen theoretical uncertainties, non-gaussian fluctuations in the response of the UA1 calorimetry or a statistical fluctuation in the data.

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Table 1: Event parameters for Events A and B.

a) 4-vectors.

		P_x (GeV/c)	P_y (GeV/c)	P_z (GeV/c)	E (GeV)	P_T (GeV/c)	N_σ^{**}
Event A	muon	10	20	-10	24	22 ± 3	9.2
	neutrino	-59 *	-53	-66	103	85 ± 11	
	jet 1	68	17	70	108	72 ± 11	
	jet 2	74	15	13	79	20 ± 4	
Event B	electron	9	-16	-10	21	19 ± 1	10.5
	neutrino	-103 *	29	-95	143	99 ± 14	
	jet 1	-93	-11	90	137	90 ± 13	
	jet 2	17	2	17	27	17 ± 4	

* P_x^V corresponding to minimum W momentum.

** $N_\sigma = E_T^{\text{miss}} / (0.7 \sqrt{E_T})$. N_σ is defined as in Ref. 18.

b) Derived parameters.

Event	P_T^W (GeV/c)	M_{jj} (GeV/c ²)	M_{Wjj} (GeV/c ²)
A	82 ± 12	82 ± 10	299 ± 28
B	105 ± 14	97 ± 12	279 ± 28

n.b. The quoted errors include resolution and $\pi^0/\pi^\pm$ response uncertainties, but do not take account of the energy scale uncertainty which is $\pm 9\%$ for the jets and $\pm 3\%$ for the electron.

Table 2: Standard Model Contributions to $l^\pm \nu jj$ Events with $P_T^W > 80 \text{ GeV/c}$ and $M(l^\pm \nu jj) > 250 \text{ GeV/c}^2$.

Process	Number of Events *
1) QCD: $W + 2 \text{ jets}$: ($e \nu + \mu \nu + \tau \nu$)	0.05 ± 0.03
2) Double Parton Scattering	$\leq 6 \times 10^{-5}$
3) Heavy Flavour Production a) $c\bar{c}$ and $b\bar{b}$ b) $t\bar{t}$	3×10^{-5} $\leq 0.02^{+0.02}_{-0.01}$
4) Associated Production of two Weak Bosons a) $q\bar{q} \rightarrow W^+ W^-$ b) $q\bar{q} \rightarrow W^\pm Z^0$ c) $H^0 \rightarrow W^+ W^-$ d) $p\bar{p} \rightarrow W^\pm H^0$	$\leq 5 \times 10^{-3}$ $\leq 5 \times 10^{-4}$ $\leq 2 \times 10^{-5}$ $\leq 9 \times 10^{-5}$
TOTAL	$\leq 0.07^{+0.05}_{-0.04} \text{ Events}$

* Quoted errors are statistical only.

Table 3: Event parameters for Event C**a) 4-vectors.**

	P_x (GeV/c)	P_y (GeV/c)	P_z (GeV/c)	E (GeV)	P_T (GeV/c)	N_σ
Z^0	59*	32	-75	137	82 ± 11	9.0
jet 1	101	-61	48	138	78 ± 12	
jet 2	-20	28	32	52	43 ± 7	

* P_x^Z corresponds to the minimum Z-jet-jet mass, assuming a $Z^0 \rightarrow \nu \bar{\nu}$ decay of a Z^0 of mass $93 \text{ GeV}/c^2$.

b) Derived parameters.

$M_{jj} \text{ (GeV}/c^2\text{)}$	148 ± 17
$M_{Zjj} \text{ (GeV}/c^2\text{)}$	$> 295 \pm 27$

REFERENCES

- [1] S. Drell and T. M. Yan, Phys. Rev. **25** (1970) 316, and Ann. Phys. **66** (1971) 578.
- [2] G. Arnison *et al.*, (UA1 collaboration), Nuovo Cimento **44** (1985) 1.
- [3] G. Arnison *et al.*, (UA1 Collaboration), Phys. Lett. **122B** (1983) 103, **129B** (1983) 273 ; G. Arnison *et al.*, (UA1 Collaboration), Phys. Lett. **134B** (1984) 469; G. Arnison *et al.*, (UA1 Collaboration), Phys. Lett. **166B** (1986) 484; G. Arnison *et al.*, (UA1 Collaboration), Europhys. Lett. **1** (1986) 327.
- [4] G. Arnison *et al.*, (UA1 Collaboration), Phys Lett. **123B** (1983) 115.
- [5] F. E. Paige and S. D. Protopopescu, ISAJET Version 5.20, BNL 38034 (1986).
- [6] M.J.Corden *et al.*, Physica Scripta, **25** (1982) 5.
- [7] The total systematic uncertainty of 9% on the jet energy scale has three components: 5% uncertainty on the absolute energy calibration; 5% on the response factor e/π as a function of energy; 5% on the Monte Carlo corrections applied to the jet algorithm results.
- [8] F. Halzen, A.D. Martin and D.M. Scott, Phys. Rev. **D25** (1982) 754 ; A. Nakamura, G. Pancheri and Y.N. Srivastava, Phys. Rev. **D29** (1984) 1936.
- [9] G. Altarelli, R. K. Ellis, and G. Martinelli, Z. Phys. C - Particles and Fields **27** (1985) 617; G. Altarelli, R. K. Ellis, M. Greco and G. Martinelli, Nucl. Phys. **B246** (1984) 12.
- [10] S. D. Ellis , R. Kleiss, and W.J. Stirling, Phys. Lett. **154B** (1985) 435.
- [11] G. Arnison *et al.*, (UA1 Collaboration), Phys. Lett. **147B** (1984) 493.
- [12] E. J. Eichten, I. Hinchcliffe, K. D. Lane ,and C. Quigg, Rev. Mod Phys. **56** (1984) 579, and references therein ; S. D. Ellis, R. Kleiss, and W. J. Stirling, Phys. Lett. **B163** (1985) 261.
- [13] P. Bagnaia *et al.*, (UA2 Collaboration), Phys. Letters **139B** (1984) 105; J. Appel *et al.*, (UA2 Collaboration), Z. Phys. C - Particles and Fields **30** (1986) 1. In these publications the UA2 collaboration reported the existence of two (electron + missing E_T + two-jet) events. Assuming W production the kinematic parameters are $m_{Wjj} \approx 150(230)$ GeV/c², $m_{jj} \approx 50$ (90) GeV/c², and $P_T^W \approx 40$ (40) GeV/c. Although initially these events appeared anomalous, further statistics favoured a standard QCD interpretation. Only the first event has a dominant missing energy contribution to the W transverse momentum. We would like to thank L.Di Lella for providing up to date information on these two UA2 events.
- [14] C. Albajar *et al.*, (UA1 Collaboration), Phys Lett. **185B** (1987) 241 .

FIGURE CAPTIONS

- Fig. 1** The transverse momentum distribution of W events. The curves show QCD predictions from Ref. [10], with extrapolations based on ISAJET (dashed lines) for $p_T^W > 60$ GeV/c.
- a) Differential distribution, $1/N \frac{1}{p_T^W} \frac{dN}{dp_T^W}$ - the data are corrected for acceptance and detector resolution.
 - b) Integral distribution, $N(p_T^W > p_T^0) / N_{\text{tot}}$ - the data are plotted at the corrected p_T^W value but are not corrected for acceptance; the theoretical prediction has been modified to take into account the acceptance corrections and the resolution on p_T^W . The bin edges mark the p_T of each event in the large p_T region and the error bars indicate the statistical uncertainty on the number of events in the bin. The latter are plotted arbitrarily at the centre of the bin. The vertical scale on the right indicates the number of observed events.
- Fig. 2** Graphic display of the calorimeter cells ($E_T > 1$ GeV) and charged tracks ($p_T > 1$ GeV/c) observed in the UA1 detector for (a) event A, and (b) event B.
- Fig. 3** Correlation between the W transverse momentum and the (W-jet-jet) mass for W plus two jet events. The curves on the projections are predictions from the explicit second order (in α_s) QCD calculation of Ref. [11] with the normalization from theory. The contours connect points of equal event density, containing respectively 68%, 95%, and 99% of the predicted events. For all curves and contours, the theory has been smeared by the jet energy resolution. The error bars on the data points are the individual resolution errors.
- Fig. 4** Correlation between the (W-jet-jet) mass and the (jet-jet) mass. The event sample and curves are as for Figure 3.
- Fig. 5** Correlation between the W transverse momentum and the (jet-jet) mass. The event sample and curves are as for Figure 3.
- Fig. 6** Graphic display of the calorimeter cells ($E_T > 1$ GeV) and charged tracks ($p_T > 1$ GeV/c) observed in the UA1 detector for event C.

FIG. 1a

FIG. 1b

$$W^+ \rightarrow \mu^+ \nu_\mu$$

EVENT A

$$p_T^W = 82 \pm 12 \text{ GeV}/c$$

$$m_{jj} = 82 \pm 10 \text{ GeV}/c^2$$

$$m_{Wjj} = 299 \pm 28 \text{ GeV}/c^2$$

FIG. 2a

EVENT B

$$p_T^W = 105 \pm 14 \text{ GeV}/c$$

$$m_{jj} = 97 \pm 12 \text{ GeV}/c^2$$

$$m_{Wjj} = 279 \pm 28 \text{ GeV}/c^2$$

FIG. 2b

FIG. 3

FIG. 4

FIG. 5

EVENT C

$$p_T^z = 82 \pm 11 \text{ GeV}/c$$

$$m_{jj} = 148 \pm 17 \text{ GeV}/c^2$$

$$m_{zjj} \geq 295 \pm 27 \text{ GeV}/c^2$$

FIG. 6