STANDARD MODEL EXPECTATIONS FOR LARGE TRANSVERSE MOMENTUM
 $W + 2$ JET EVENTS AT THE CERN COLLIDER

R. Kleiss and W.J. Stirling ¹⁾

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Abstract

The bulk of the UA1 sample of W events can be well understood in the standard model. The two events with the largest W transverse momentum are, however, rather unusual. In each event there are two jets and the invariant masses of the jet-jet and W -jet-jet systems are large. We use the appropriate QCD matrix elements to calculate the expected number of events of this type, and find a substantial discrepancy between the predicted and observed rates. We are therefore led to consider a scenario where the events are due to a new heavy particle, with a mass on the order of 250 GeV/c^2 , which decays predominantly into W^+W^- .

¹⁾ Physics Department, University of Durham, Durham, England

The study of W and Z events with jet activity in $p\bar{p}$ collisions at the CERN collider has provided some important tests of perturbative QCD. The fraction of events with different numbers of jets, the angular and transverse momentum distribution of the jets and the transverse momentum of the weak bosons can all be quantitatively understood in terms of the higher order QCD subprocesses involving the emission of additional quarks and gluons, $q\bar{q} \rightarrow Wg$ etc [1] [2].

The UA1 collaboration has recently reported a sample of several hundred W events [1]. The bulk of these can be well understood in the standard model. Two unusual events, however, stand out from the rest. In each of the $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ samples the event with the largest W transverse momentum contains two jets - the naive expectation would be one - and the mass of the W -j-j system is very large. Both events appear quite isolated from the rest of the sample and are characterised by well separated energetic final state leptons and jets [1].

In this letter we assess the likelihood that these events have a standard model origin; that is, we calculate the expected cross-sections for events of this type. We find that the predicted rate is roughly an order of magnitude smaller than the rate observed. Of course with only two events it is impossible to draw any firm conclusion. Nevertheless it is interesting and informative - not least for the analysis of future data - to be guided by the event topologies themselves and to consider the possibility that the

events are signatures of a new heavy particle, which we shall call Z' , produced in $q\bar{q}$ annihilation and decaying predominantly into WW pairs. In a relatively model independent way we describe a scenario for the Z' mass and couplings which could "explain" the two unusual events.

The calculation of W +jets cross-sections described below follows the methods of [3]. Unless otherwise stated, all cross-sections include the W decay mode $W \rightarrow e\nu$ and are evaluated at $\sqrt{s} = 630$ GeV, using Duke-Owens set 1 structure functions with scale $Q^2 = \hat{s}$. The rapidity, transverse momentum and separation cuts imposed on the leptons and jets are typical of those of UA1 and are listed in [3]. As always, such theoretical cross-sections suffer from a normalisation uncertainty. We gauge this by repeating the calculations using a smaller scale $Q = M_W$ and Duke-Owens set 2 structure functions, which gives systematically larger rates.

We start by considering the cross-section for $W+2j$, calculated from the subprocesses $q\bar{q} \rightarrow Wgg$, $qg \rightarrow Wqg$, With the standard cuts we find

$$\sigma \cdot B^{W \rightarrow e\nu} = 17 \text{ pb} \quad (1)$$

With an integrated luminosity of $.73 \text{ pb}^{-1}$, this corresponds to 12.4 events which compares favourably with the observed number of 15 two jet events for the complete $W \rightarrow e\nu$ UA1 sample [1]. This agreement lends further support to the theoretical cross-sections which follow. We now proceed to systematically tighten the cuts to correspond to the topology of the two

events. Fig.1 shows the P_T^W distribution for the above $W+2j$ cross-section. Requiring that P_T^W be greater than 60 GeV/c yields

$$\sigma \cdot B \Big|_{P_T^W > 60 \text{ GeV/c}} = 0.23 \text{ pb} \quad (2)$$

This number is to be contrasted with the corresponding cross-section for $W+1j$:

$$\sigma^{W+1j} \cdot B \Big|_{P_T^W > 60 \text{ GeV/c}} = 0.47 \text{ pb} \quad (3)$$

Figs.2(a) and 2(b) show the distribution in M_{Wjj} and M_{jj} respectively for the large P_T^W $W+2j$ events. Both distributions are quite broad and peak respectively at 190 GeV and 40 GeV as a result of the kinematical cuts. To define a region of phase space which well-contains the unusual events we further require that

$$\begin{aligned} M_{Wjj} &> 200 \text{ GeV/c}^2 \\ M_{jj} &> 60 \text{ GeV/c}^2 \\ P_T^j &> 10 \text{ GeV/c} \end{aligned} \quad (4)$$

This leads to a final cross-section estimate of

$$\sigma \cdot B \Big|_{\text{all cuts}} = 0.05 \text{ pb} \quad (5)$$

We have deliberately chosen the above rather conservative cuts to allow for possible measurement uncertainties in the transverse momenta and invariant masses. The preliminary values for these event parameters reported in [1] satisfy the above inequalities. The corrected values reported more recently [4] are even larger, making our estimates even more optimistic. From the distributions in Figs.1 and 2, it is straightforward to infer how our results would change if the cuts were relaxed or tightened. Table 1 gives the corresponding cross-sections for larger P_T^W and mass cuts. As expected the predicted rates fall quite rapidly. With the choice of scale $Q = M_W$ and DO2 structure functions we obtain slightly larger rates; the total $W+2j$ cross-section rises to 24 pb (17.4 events) and the cross-section after all cuts described above becomes 0.11 pb.

We have characterised our analysis in terms of the three variables M_{Wjj} , M_{jj} , and P_T^W . It is important to realise that any two of these can essentially be regarded as "independent" variables. In other words, a large value for one does not necessarily imply a large value for the others. As an illustration, consider the case of a W -jet-jet system of fixed large invariant mass, say 250 GeV/c². The transverse momentum of the W can then range from 0 (W at rest with two jets of energy 84 GeV) to a theoretical maximum of 112 GeV/c (W transverse momentum balanced by two collinear transverse jets). In fact for this value of the total invariant mass the full QCD calculation gives a P_T^W distribution which is quite broad, with a peak around 30 - 40 GeV/c. Thus the cuts of (4) - which are meant to characterise the two UA1 events - lead to a double suppression of the cross-section; first from requiring large M_{Wjj} and second from requiring large P_T^W .

The fact that in both events the mass of the jet pair is near M_W naturally leads to another possible standard model origin :

$$p + \bar{p} \rightarrow W + W + \dots$$

$$\quad \quad \quad \downarrow \quad \quad \downarrow$$

$$\quad \quad \quad l\nu \quad \quad jj$$
(6)

This process has been much studied in the context of supercollider physics [5] and it is straightforward to adapt the calculation [6] to the present situation. Following the analysis of [6] we find however that the predicted rate is very small. With no cuts on P_T^W , M_{Wjj} or M_{jj} we find

$$\sigma^{WW} \cdot B = 0.03 \text{ pb}$$
(7)

Further cuts of $P_T^W > 60 \text{ GeV}/c$, $M_{Wjj} > 200 \text{ GeV}$ and $M_{jj} > 60 \text{ GeV}$ reduce this to

$$\sigma^{WW} \cdot B \Big|_{\text{all cuts}} = 0.004 \text{ pb}$$
(8)

Note that we have not included the small contribution from WZ production. The rate for this is known to be about a factor of 3 smaller than for WW, with about the same branching ratio to $evjj$ [5]. In principle the production and weak decay of heavy quarks can also lead to events with jets, leptons and missing energy, but we estimate that the rate (e.g. from bottom, top) would be negligible inside the tight cuts listed above. Combining

(5) and (8), we therefore conclude that the theoretical estimate of events of this type is .04 - .08 per lepton flavour, for an integrated luminosity of $.73 \text{ pb}^{-1}$.

Although the above analysis has demonstrated that there is a large discrepancy between the expected and observed rate, any definite conclusion must await more statistics. It is very possible that the two events are simply the tail of a distribution that has yet to be "filled in". However it is interesting in the meantime to speculate on other possible non-standard sources. The preliminary values for the event parameters presented in [1] show that for both events the invariant mass of the W-jet-jet system is in the 250-300 GeV/c^2 range and, further, that the jet-jet mass is of order M_W . Suppose then, for sake of illustration, that the events are due to the production and decay of a new heavy particle Z' . The following properties then follow: (a) $M_{Z'}$ must be of order 200-300 GeV/c^2 , (b) the decay $Z' \rightarrow WW$ must dominate and (c) Z' must have a sizeable coupling to light quarks or gluons to give a large enough production rate. The standard model scalar Higgs, for example, could pass (a) and (b) but would then fail (c). In order to set a benchmark we consider the following scenario: Z' is essentially a heavy Z , with $M_{Z'} > 2 M_W$, which has the same couplings to fermions and W 's as the usual light Z . With this assumption it is straightforward to calculate the production cross-section $q\bar{q} \rightarrow Z'$ and the decay branching ratios $Z' \rightarrow WW$, $f\bar{f}$.

For the latter we find

$$\Gamma(Z' \rightarrow WW) = \frac{\alpha \cot^2 \theta_w}{48} M_{Z'} x^{-3} (x^2 - 4)^{3/2} \cdot (x^4 + 20x^2 + 12)$$

$$x = \frac{M_{Z'}}{M_W}$$

$$\Gamma(Z' \rightarrow f\bar{f}) = \frac{M_{Z'}}{12\pi} \left\{ (g_V^f)^2 + (g_A^f)^2 \right\}$$

$$m_f = 0 \quad (9)$$

Fig.3 shows the branching ratios thus obtained as a function of $M_{Z'}$. In particular, a 250 GeV/c² Z' has a total width of 25 GeV, with a 70% branching ratio into WW and thus a 7% branching ratio into a $evjj$ final state ($j=u,d,s,c$).

We have calculated the cross-sections for Z' production and decay, incorporating explicitly the hadronic and leptonic W decays. With the same basic cuts as before (i.e. no cuts on P_T^W , M_{Wjj} and M_{jj}) we find

<u>$M_{Z'} \text{ (GeV/c}^2\text{)}$</u>	<u>$\sigma_{Z'} \cdot B \text{ (pb)}$</u>
200	0.96
250	0.41
300	0.10

(10)

Fig.4 shows the corresponding $M_{Wjj} = M_{WW}$ and P_T^W distributions. The P_T^W distribution shows a broad Jacobian peak centred around 90 GeV/c.

Thus for a 250 GeV/c² Z' with the above couplings we expect about .3 event per lepton flavour in a sample of .73 pb⁻¹. Note that we have not included the K-factor correction to the production cross-section which would be expected to give a 30% increase. It is straightforward to estimate the rate for a different choice of couplings. For example, increasing both the $Z'ff$ and $Z'WW$ couplings by a factor λ would give the same branching ratios but would increase both the production cross-section and the width by a factor λ^2 . It is interesting to note that the simultaneous requirements that the particle be reasonably narrow but have a large enough production rate restricts λ to be not too different from 1.

The above analysis shows that a 250 GeV/c² Z' with near standard couplings is roughly compatible with the two observed events in both rate and topology. It is next important to investigate whether a measurable effect could be observed in other channels. The branching ratio into e^+e^- or $\mu^+\mu^-$ pairs (1%) puts this channel below the level of observability. UA1 have already put a lower (90% cl) limit of 166 GeV on a heavy Z' with a standard (3%) branching ratio into e^+e^- [1]. The decay into light quark jet pairs (7%) would be unobservable because of the large rate from QCD 2→2 jet pairs. A more significant signal is the 4 jet decay mode of the WW pair. The UA2 collaboration has recently reported a study of 4 jet events [7]. The overall rate is roughly compatible with the rate expected from QCD 2→4 parton scattering subprocesses [8]. The question is now whether a Z' signal would be observable in the relevant 4 jet mass range.

We have calculated both the QCD 4 jet background and the $Z' \rightarrow 4j$ signal using a set of tight jet cuts similar to those used by UA2, i.e. $|\eta_j| < 0.8$, $P_T^j > 15$ GeV/c and $\theta_{jj} > 50^\circ$. We obtain a total QCD 4 jet cross-section of .20 nb. The distribution in M_{4j} is shown in Fig.5 together with the $Z' \rightarrow WW \rightarrow 4j$ signal calculated using the same couplings as before. Considering the considerable theoretical normalisation uncertainty in both the signal and background, it is not possible to draw any definite conclusion from Fig.5. For example, if one wished to calibrate the "predicted" $\lambda_{\nu jj}$ rate ($1/3 - 1/2$ event) to the observed rate (1 event) one would increase the signal in Fig.5 by a factor 2 - 3. However it is certainly worth analysing the 4 jet data to look for any evidence of a flat tail or even a peak in the 4 jet mass distribution. An excess of large mass events could be identified by renormalising the QCD 4 jet curve to fit the lower mass events. Note also that tight jet cuts automatically enhance the signal over the QCD background, since the QCD jets have a preference to be soft and emitted close to each other and to the beam direction. With enough statistics, further cuts - for example requiring that there be two jet pairs of comparable invariant mass - could usefully be imposed to further enhance any possible Z' signal.

In conclusion, we have shown how it is difficult to reconcile the two largest P_T^W events with standard model expectations. With rather conservative cuts we would expect only about $.06 \pm .02$ events for each lepton flavour. There is therefore the possibility that the events are a signal for new phenomena. We have shown how a heavy Z with mass on the order of 250 GeV/c² and standard couplings to W 's and fermions can account for the rate and topology of the events. As always, more statistics will confirm or

refute this hypothesis. In the meantime, a careful study of the 4 jet sample may yield more information.

Finally, it has been pointed out [4] that one of the events in the UA1 missing energy sample has a very similar jet topology to the two W events discussed above. In particular, the event has large missing transverse energy balanced by two jets of large invariant mass. The topology is suggestive of a heavy state decaying into two Z's which subsequently decay into jets and neutrinos respectively. We have not included this event in our discussion because of the difficulties involved in modelling the experimental missing energy selection. A crude calculation of the background expected from the standard model process $p\bar{p} \rightarrow Z + 2 \text{ jets}$ yields $.07 \pm .02$ events with $E_T^{\text{miss}} > 60 \text{ GeV}$ and $M_{jj} > 60 \text{ GeV}$. Of course a Z' such as that discussed above would not make any significant contribution to this missing energy channel.

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References

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$P_T^W > 60 \text{ GeV/c}$		$M_{Wjj} >$		
		200	250	300
$M_{jj} >$	60	0.049	0.019	0.004
	80	0.027	0.014	0.003

$P_T^W > 80 \text{ GeV/c}$		$M_{Wjj} >$		
		200	250	300
$M_{jj} >$	60	0.014	0.010	0.003
	80	0.008	0.006	0.002

Table 1 : QCD cross sections for $W + 2 \text{ jet}$ events with (a) $P_T^W > 60 \text{ GeV/c}$ and (b) $P_T^W > 80 \text{ GeV/c}$ for different mass thresholds (masses in GeV/c^2 , cross-sections in pb).

Figure Captions

Fig.1

W transverse momentum distribution for the QCD W + 2 jet cross section.

Fig.2

(a) M_{Wjj} and (b) M_{jj} distributions for W + 2 jet events with $P_T^W > 60$ GeV/c.

Fig.3

(a) Branching ratios and (b) total width of a hypothetical heavy Z particle with standard couplings to W's and fermions, as a function of its mass. Three generations and a top quark mass of 40 GeV/c² are assumed.

Fig.4

(a) M_{WW} and (b) P_T^W distributions for a Z' of mass 250 GeV/c² decaying into two W's.

Fig.5

M_{4j} distribution expected from QCD 2→4 scattering (upper histogram), and from a 250 GeV/c² Z' decaying into two W's which subsequently decay hadronically (lower histogram). The cuts are described in the text.

Fig.1

Fig.2

Fig.3

Fig.4

Fig.5