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OBSERVATION OF ELECTRONS
PRODUCED IN ASSOCIATION WITH HARD JETS
AND LARGE MISSING TRANSVERSE MOMENTUM
IN $p\bar{p}$ COLLISIONS AT $\sqrt{s} = 540$ GeV

The UA2 Collaboration

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ABSTRACT

Using a sample of events collected by UA2 and corresponding to an integrated luminosity of 116 nb^{-1} , we have searched for electron-"neutrino" pairs in which the transverse momenta of the electron and of the "neutrino" exceed $15 \text{ GeV}/c$ and $25 \text{ GeV}/c$ respectively. A total of 35 events are observed in low background conditions. Most events can be interpreted in terms of W^+ production from QCD processes. Events in which the observation of hard jets makes this interpretation unlikely are described in detail. Possible sources of background contamination are considered.

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1. INTRODUCTION

In another publication [1], we have studied a sample of events recorded by UA2 [2] at the Sp $\bar{p}$ S collider [3], which contain an electron candidate in the final state with a transverse momentum $p_{\perp}(e)$ in excess of 15 GeV/c. This sample includes events having a genuine electron in the final state as well as a contamination of background events for which the electron identification is erroneous. In the former category we expect, from lepton number conservation, that the electron is associated with another electron of opposite charge or with a neutrino. We have reported elsewhere [4] on the 8 events containing an electron pair in the final state, all associated with the production and decay of the electroweak boson Z^0 . We have also reported [1] on events containing an electron-neutrino pair in the final state, and we have given a detailed analysis of these events in terms of the production and decay of the electroweak bosons $W^{\pm}$. This latter analysis discarded events in which a significant amount of transverse energy was detected at opposite azimuth to the electron candidate. This procedure efficiently rejected two-jet events in which one of the jets was misidentified as an electron. Other events, however containing a genuine electron in the final state, may have also been rejected by this cut.

The purpose of the present letter is to report on a systematic search for events containing an electron-"neutrino" pair in the final state, whatever the transverse energy at opposite azimuth to the electron may be. The loss of rejection power against background, resulting from having relaxed this constraint, is compensated by the requirement that both the electron and the "neutrino" have large transverse momenta.

Our detector does not distinguish between a neutrino and other possible non-interacting particles, such as the photino postulated by supersymmetry theories [5]. In the remainder of this letter the word "neutrino" must therefore be understood in a broad sense.

2. APPARATUS

The UA2 detector has been described in detail elsewhere [2]. We briefly recall its main features.

Apart from two narrow cones along the beams, the detector provides full azimuthal coverage in three distinct regions of polar angles : $40^\circ < \theta < 140^\circ$, the central region, and $20^\circ < \theta < 40^\circ$, $140^\circ < \theta < 160^\circ$, the forward regions.

In the centre of the detector a set of coaxial cylindrical drift and proportional chambers detect the charged particles produced in the collision and measure the position of the event vertex.

An array of 480 calorimeter cells, each cell covering a similar domain of longitudinal phase-space (15° of azimuth and ≈ 0.2 units of rapidity), measures electron energies $E(e)$ to a good accuracy. Each cell is segmented longitudinally to provide electron-hadron separation. While hadron showers are usually contained in the 4.5 absorption lengths of the central calorimeter, providing a measurement of jet energies, they only deposit a fraction of their energy in the forward calorimeters which are ≈ 1.0 absorption length thick. These forward regions are equipped with magnetic spectrometers which provide additional rejection power against hadrons and converted photons when searching for electrons. In addition they measure the momenta of charged jet fragments, the energy of π^0 's being measured in the calorimeter cells.

In both the central and forward regions electron identification is significantly improved by preshower counters which accurately measure the match between the observed incident track and the developing shower.

3. DATA SAMPLE

The present analysis deals with the sample of 225 events containing an electron candidate having $p_{\perp}(e) > 15 \text{ GeV}/c$ and obeying the selection criteria described in Table 1 of Ref.1. This event sample corresponds to an integrated luminosity of 131 nb^{-1} . We discard from this sample events collected in the 1982 period, during which the azimuthal coverage of the UA2 detector was incomplete [2]. We also discard 10 events in which the electron candidate is observed near the interface between the central region and one of the forward regions and is associated with nearby calorimeter energy in each of the two regions. In such cases, when the electron candidate is in fact a misidentified jet, a significant fraction of the jet energy is likely to be lost in the magnet coils at the interface of the two regions and may simulate a neutrino. Together, the initial sample is reduced to 190 events, and the corresponding integrated luminosity to 116 nb^{-1} .

The global detection efficiency of the electron selection criteria is estimated [1] to be 80% in the forward regions and 76% in the central region.

In each event we reduce the final state to a set of transverse energy clusters according to simple algorithms which have been described elsewhere [1,2]. One of the clusters is associated with the electron candidate. Each of the other clusters is usually associated with a multiparticle jet provided that it carries large transverse energy. For this reason, in what follows, we shall call "jets" clusters having a transverse energy in excess of 3 GeV.

For each event we calculate the momentum $\vec{p}$ (transverse component $\vec{p}_{\perp}$ and longitudinal component $p_{\parallel}$) and energy E of the electron candidate (e) and of each individual jet (j) assumed to be massless. We also evaluate the momentum $\vec{p}$, energy E and mass m of various sets of particles such as the system of all jets (J) or the system of electron and jets, (Je). The quantity $p_{\perp}(Je)$ measures the missing transverse momentum in the set of all detected particles resulting in clusters having $E_{\perp} > 3 \text{ GeV}$. In a typical event, the softer particles carry

together only a small transverse momentum and, if no large transverse momentum particle has escaped detection, the observation of a large $p_{\perp}(\text{Je})$ reveals the presence of a neutrino (ν) with $p_{\perp}(\nu) \approx p_{\perp}(\text{Je})$.

The distribution of $p_{\perp}(\text{Je})$ is shown in Fig.1a. The background evaluation follows the method described in Ref.1 and measures the probability that a multijet event contains both a misidentified electron and an undetected jet (or jets) escaping the UA2 acceptance. Its distribution is shown as a curve superimposed on the data of Fig.1a. The background contribution amounts to 10.0 ± 0.9 events for $p_{\perp}(\text{Je}) > 20$ GeV/c, 3.4 ± 0.3 events for $p_{\perp}(\text{Je}) > 25$ GeV/c and 1.2 ± 0.1 events for $p_{\perp}(\text{Je}) > 30$ GeV/c.

In the remainder of this letter we restrict the analysis to the sample of 35 events which have $p_{\perp}(\text{Je}) > 25$ GeV/c, and which are therefore candidates for containing a large transverse momentum neutrino in the final state.

4. DATA ANALYSIS AND BACKGROUND EVALUATION

From the results of the analysis presented in Ref.1 we expect our sample to contain a number of events in which the observed electron carries most of the detected transverse energy, and is therefore accompanied by no jet or by jets having small transverse energies. The distribution of the sum of the jet transverse energies, $E_{\perp}(\text{J})$, confirms this expectation (Fig.1b). The 31 events having $E_{\perp}(\text{J}) < 30$ GeV all belong to the samples of Figs. 4a and 4c in Ref.1, where they were interpreted in terms of $W \rightarrow e\nu$ decays. We do not comment further on these events. Instead we consider the four events having $E_{\perp}(\text{J}) > 30$ GeV. The distribution of the events in the $p_{\perp}(\text{Je}), E_{\perp}(\text{J})$ plane is shown in Fig.2 for each of the signal and background samples. The background contamination expected in the region $p_{\perp}(\text{Je}) > 25$ GeV/c, $E_{\perp}(\text{J}) > 30$ GeV is $\approx 0.45 \pm 0.04$ events. In each of the four signal events the electron candidate is detected in the central region of the UA2 detector. Their transverse momentum configurations are illustrated in Fig.3.

For each event, in which $p_1(\text{Je})$ and $E_1(\text{J})$ take values p_0 and E_0 respectively, we evaluate the expected background contaminations B_1 and B_2 corresponding to the following configurations :

$$B_1 : p_1(\text{Je}) > p_0, E_1(\text{J}) > 30 \text{ GeV},$$

$$B_2 : p_1(\text{Je}) > 25 \text{ GeV}/c, E_1(\text{J}) > E_0.$$

In each of the four events, either B_1 or B_2 is always less than 0.02. It is remarkable that there is no background event in the region $p_1(\text{Je}) > 50 \text{ GeV}/c$, $E_1(\text{J}) > 30 \text{ GeV}$, which contains events A to C. We infer from this a background contamination of at most 0.02 events (90% confidence level) in this region.

As a check on the quality of the electron identification we compare in Fig.4 the values taken by a few characteristic parameters in the present sample and in the sample of $W \rightarrow e\nu$ candidates having $p_1(e) > 25 \text{ GeV}/c$ [1]. Each of the four events has been examined in detail with the help of a high resolution graphics display facility. The track multiplicity is of course higher here than in most of the $W \rightarrow e\nu$ events studied in Ref.1 and we cannot exclude that the increased complexity of the signal pattern in the central vertex detector could result in some deterioration of the electron identification power.

As far as neutrino identification is concerned, we have checked that in each of the four events there is no sign of large transverse momentum particles having hit passive parts of the UA2 detector, such as the magnet coils, in the azimuthal region where the neutrino is expected. However, in the case of event D which has an azimuthal configuration similar to that of a two-jet event, such an interpretation cannot be completely excluded.

Large transverse momentum particles may have escaped detection because they were produced at small angle to the beam line. We considered for each event the possibility that a jet having the same transverse momentum as the neutrino candidate be produced at $\theta = 15^\circ$ (or 165°). Under such an assumption we can calculate a lower limit for

the invariant mass of the system of all large transverse momentum particles produced in the event, including the small angle undetected jet. In the case of events A to C they correspond to impossible or very unlikely kinematical configurations.

More generally an event appearing at (p_0, E_0) in the $p_1(\text{Je}), E_1(\text{J})$ plane (Fig.2) may be interpreted as containing an undetected jet which would account, at least in part, for the measured value of p_0 . If this jet had been detected, the same event would have appeared at (p'_0, E'_0) with $p'_0 < p_0$ and $p'_0 + E'_0 \geq p_0 + E_0$. But the only events having $p_1(\text{Je}) + E_1(\text{J}) > 90$ GeV are precisely the four events of Fig.3. The absence of other events in this region, even with low values of $p_1(\text{Je})$, excludes such an interpretation.

A muon can in principle simulate a neutrino in the UA2 detector. Although we know of no mechanism which could produce a very massive electron-muon pair at a detectable rate, we looked, in each of the four events, for a track in the vertex detector near the neutrino azimuth and associated with calorimeter energy consistent with the response to a minimum ionizing particle. We found none.

In each of the four events in Fig.3 the sharing of the jet energies between the various calorimeter compartments [2] is consistent with expectation. Moreover, each jet contains several tracks having their origin at the event vertex. These observations exclude interpretations in terms of a cosmic ray or beam-gas background.

5. EVENT INTERPRETATION

In this section we study possible sources for events A to D, under the assumption that they contain a genuine $e\nu$ pair.

While in three events (A to C) the $e\nu$ pair has a large azimuthal opening ($\Delta\phi > 120^\circ$), event D contains a narrow $e\nu$ pair ($\Delta\phi \approx 17^\circ$). It consists of a large transverse momentum jet ($p_\perp(j_1) \approx 70 \text{ GeV}/c$) emitted at opposite azimuth to the electron-neutrino pair and to a smaller transverse momentum jet ($p_\perp(j_2) \approx 25 \text{ GeV}/c$). The invariant mass of the $(e\nu j_2)$ system depends upon the unknown value of $p_\parallel(\nu)$. It takes its minimum value, $23 \pm 6 \text{ GeV}/c^2$, when the neutrino has the same rapidity as the (ej_2) system. In this case $m(e\nu j_1 j_2) = 145 \pm 15 \text{ GeV}/c^2$. The configuration of this event suggests an interpretation in terms of a quark-antiquark pair, one member of which decays semileptonically. However, because of the absence of other events with similar topologies and because of the similarity of its configuration with that of a two-jet event, we prefer to defer such an interpretation until other events of the same kind have been observed.

In the three other events (A to C) the transverse mass of the $e\nu$ pair (Table 1) ranges between $56 \text{ GeV}/c^2$ and $82 \text{ GeV}/c^2$, suggesting an interpretation in terms of a $W \rightarrow e\nu$ decay, the W boson being the only known particle with a large enough mass. It is indeed possible to adjust the unknown value of $p_\parallel(\nu)$ to obtain $m(e\nu) = m(W)$ and to describe the events in terms of associated W -jet(s) production. There are in general two solutions to this problem, associated with different values of $p_\parallel(WJ) \equiv x_F(WJ)\sqrt{s}/2$ and of $m(WJ)$, which are listed in Table 1. The distribution of $m(WJ)$ for the solution giving the smaller value of $|x_F(WJ)|$ is shown in Fig.5 for all events having $p_\perp(Je) > 25 \text{ GeV}/c$. While the 31 events having $E_1(J) < 30 \text{ GeV}$ cluster in the neighbourhood of $m(WJ) = m(W)$, the three events of Table 1 populate the region $160 \leq m(WJ) \leq 180 \text{ GeV}/c^2$, which might suggest an interpretation in terms of a heavy object decaying into a W boson and a system J of other particles. However, the significance of this observation is weakened by the fact that the background events have a similar $m(WJ)$ distribution (Fig.5), implying that the clustering in mass might simply

result from kinematics. In addition such an interpretation should account for the fact that in events A and B, J consists essentially of a single jet, while in event C it consists of a large mass pair of jets.

We remark that a reasonable upper limit to the rate of occurrence of events containing a $W \rightarrow e\nu$ produced via known processes in association with a system J of large transverse momentum jets can be obtained from the relation

$$\begin{aligned} \sigma(p\bar{p} \rightarrow W + J + \dots) / \sigma(p\bar{p} \rightarrow W + \dots) &\approx \\ \approx \sigma(p\bar{p} \rightarrow j_1 j_2 + J + \dots) / \sigma(p\bar{p} \rightarrow j_1 j_2 + \dots) \end{aligned}$$

where $j_1 j_2$ is a pair of jets having the same configuration as the $e\nu$ pair ascribed to a W decay. This relation holds approximately for processes in which $j_1 j_2$ couples via a gluon to a quark-antiquark pair (although the W -current, contrary to the gluon-current, is flavour changing). We expect the contribution of other QCD subprocesses, and interferences among them, to alter only slightly the right hand side of the above relation. We evaluate such upper limits for events A to C from the sample of jet events described in Ref.6. We take as J any jet (jet pair) having a transverse momentum (invariant mass) at least as large as that of the corresponding jet (jet pair) in events A and B (C).

The results, listed in Table 1, include the different acceptances of the UA2 apparatus to $e\nu$ pairs and to jet pairs. They indicate that events B and C, if they indeed contain a genuine $W \rightarrow e\nu$, are difficult to understand in terms of associated W -jet(s) production via known processes. Event A, on the other hand, has an unlikely high value of $x_F(WJ)$, corresponding to a W longitudinal momentum of nearly 150 GeV/c.

More generally we note that if the $e\nu$ pair in events A to C is coupled to the initial state via a real or virtual W , as expected in standard theories, other events in which the $e\nu$ pair is replaced by a jet pair should occur as well, at a rate at least 6 times as high (for the two lighter quark families). However, this factor is reduced by acceptance effects and a search for such events is beyond the scope of the present letter.

The uncertainties quoted in Table 1 account for measurement errors on energies and angles. The neutrino transverse momentum may be evaluated from the large transverse momentum particles alone, $\bar{p}_1(\nu) = -\bar{p}_1(Je)$, or by including all other softer particles which do not result in transverse energy clusters exceeding 3 GeV. The differences between the two evaluations are small and have been accounted for in Table 1.

In addition to the above instrumental uncertainties, the measured jet energies are expected to be somewhat smaller than that of the parent partons (we neglect the jet mass and we do not include jet fragments which do not contribute to the transverse energy cluster). These effects are not corrected for in Table 1. Using the ISAJET programme [7] to simulate W decays into a pair of light quarks, we find that the measured two-cluster mass is expected to be ≈ 15 GeV/c² lower than $m(W)$. Therefore the value $m(J) = 63 \pm 5$ GeV/c² obtained for event C is not inconsistent with the hypothesis that J results from a W decay.

Finally we note that the interpretation of the $e\nu$ pair in terms of a W decay in events A to C is by no means mandatory because the missing transverse momentum does not need to be ascribed to a single neutrino but might be shared among several undetected particles.

6. CONCLUSION

A search for events containing an electron-neutrino pair having $p_1(e) > 15$ GeV/c and $p_1(\nu) > 25$ GeV/c has resulted in a sample of 35 events, the majority of which have been previously studied [1] and interpreted in terms of $W^\pm$ production, with characteristic properties in agreement with QCD predictions.

Four events have been found, in which the $e\nu$ pair is produced in association with a jet, or a system of jets, having very large transverse energies. We have given a detailed description of these events and we have considered possible sources of background contaminations.

Three of these events contain a large transverse mass ev pair and have been interpreted in terms of W -jet(s) associated production. However, their configurations are such that their production via known processes is very unlikely for at least two of them. In each of the three events the invariant mass of the W -jet(s) system is measured to be in the vicinity of $170 \text{ GeV}/c^2$, but the significance of this observation is weakened by the fact that this mass region is kinematically favoured by the selection criteria.

Interpretations in terms of new processes, including the possibility of ascribing the observed missing transverse energy to particles other than a single neutrino, have not been explicitly considered.

While the present study indicates that we have observed events corresponding to a genuine signal and suggests the existence of a new phenomenon, more data need to be collected in order to place this result on firmer ground.

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Table 1 : Event parameters

Events		A	B	C	Units
Electron	$p_T(e)$	18.3 ± 0.8	22.0 ± 0.9	34.4 ± 3.2	GeV/c
	$\eta(e)$ a)	0.02	-0.23	0.24	
	$P(\chi^2)$ b)	0.97	0.76	0.002	
	d^2 b)	13	7	14	mm^2
	q_5 b)	10	8	22	mip
Jets ^{f)}	$p_T(j_1)$	27 ± 3	67 ± 7	38 ± 5	GeV/c
	$\eta(j_1)$ a)	-0.59	-0.26	0.07	
	$\Delta\phi(j_1)$ c)	50	310	311	degrees
	$p_T(j_2)$	6 ± 1		21 ± 3	GeV/c
	$\eta(j_2)$ a)	0.50		0.12	
	$\Delta\phi(j_2)$ c)	93		183	degrees
	$p_T(j_3)$	5 ± 1		7 ± 1	GeV/c
	$\eta(j_3)$ a)	-1.09		-1.38	
	$\Delta\phi(j_3)$ c)	70		316	degrees
	$E_T(J)$	39 ± 4	67 ± 7	66 ± 6	GeV
	$m(J)$			63 ± 5	GeV/c^2
	$p_T(\nu)$	51 ± 4	86 ± 6	57 ± 5	GeV/c
	$\Delta\phi(\nu)$ c)	220	141	141	degrees
	$m_T(\text{ev})$	56 ± 2	81 ± 3	82 ± 4	GeV/c^2
	1 $\left\{ \begin{array}{l} m(WJ) \\ x_F(WJ) \end{array} \right.$	179 ± 7 0.45 ± 0.04	176 ± 9 -0.01 ± 0.06	162 ± 8 -0.04 ± 0.05	GeV/c^2
	2 $\left\{ \begin{array}{l} m(WJ) \\ x_F(WJ) \end{array} \right.$	141 -0.55	166 -0.31	164 0.13	GeV/c^2
	B_1 d)	<0.016(90%CL)	<0.016(90%CL)	<0.016(90%CL)	
	B_2 d)	0.33 ± 0.03	0.06 ± 0.01	0.06 ± 0.01	
	N_{QCD} e)	0.4	$1.2 \cdot 10^{-2}$	$7 \cdot 10^{-3}$	

a) The pseudo-rapidity η is positive in the proton direction.

b) Electron quality parameters are defined in Fig. 4 and Ref. 1.

c) $\Delta\phi$ is the azimuth difference with respect to the electron (in degrees).

d) Background evaluations B_1 and B_2 are described in the text (Section 4).

e) Number of W-jets events expected from known production processes (see text).

f) Jet energies are expected to be smaller than the parent parton energies (see text). This has not been corrected for and affects all parameters depending upon jet energies.

FIGURE CAPTIONS

1. a) Transverse momentum distribution of the system of electron and jets in the initial sample of 190 events.
 b) Transverse energy distribution of the system of jets in the sample of 35 events having $p_1(\text{Je}) > 25 \text{ GeV}/c$. The event at $E_1(\text{J}) \approx 26 \text{ GeV}$ is the largest transverse momentum W in Fig.8 of Ref.1.

The lines correspond to the calculated background contaminations. The four events having $p_1(\text{Je}) > 25 \text{ GeV}/c$, $E_1(\text{J}) > 30 \text{ GeV}$, are cross-hatched.

2. a) Distribution of the 190 events of the initial sample in the $p_1(\text{Je}), E_1(\text{J})$ plane. Seven Z^0 events are circled (the eighth one was collected during the 1982 period, see Ref.4). The W region is indicated.
 b) Distribution of the background sample in the $p_1(\text{Je}), E_1(\text{J})$ plane. A reduction factor of 141 must be applied to infer from this sample the background contamination to the sample of Fig.2a.

Lines of constant $p_1(\text{Je}) = 25$ and $50 \text{ GeV}/c$, $E_1(\text{J}) = 30 \text{ GeV}$ and $p_1(\text{Je}) + E_1(\text{J}) = 90 \text{ GeV}$ are indicated.

3. Transverse momentum configuration of the four events having $p_1(\text{Je}) > 25 \text{ GeV}/c$ and $E_1(\text{J}) > 30 \text{ GeV}$. Their relative orientation is arbitrary.
4. Electron quality parameters (see Ref.1) :
 - a) quality of the track-cluster match,
 - b) ionisation measured in minimum ionising particle equivalent (mip). This information is not available for event D.
 - c) distance squared from the track to the preshower counter cluster centroid (measured in mm^2),
 - d) charge of the preshower counter cluster (measured in mip).

The histograms are for the $W \rightarrow e\nu$ candidates presented in Ref.1 and having $p_1(e) > 25 \text{ GeV}/c$. The values taken by the

quality parameters of the four events in Fig.3 are indicated by arrows.

5. Distribution of $m(WJ)$ for the 35 events having $p_1(Je) > 25$ GeV/c. Events having in addition $E_1(J) > 30$ GeV are cross-hatched. The event at $m(WJ) \approx 120$ GeV/c² is the event having $E_1(J) \approx 26$ GeV (see Fig.1b and Ref.1). Event D is omitted from the figure because its narrow ev pair does not suggest an interpretation in terms of $W \rightarrow ev$. Such an interpretation would imply a very large value of $p_1(W)$ and $m(WJ) \approx 230$ GeV/c². The smooth line corresponds to the calculated background. The dotted line is the background distribution (multiplied by 100) for events having $E_1(J) > 30$ GeV.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5