14 October 1983

SEARCH FOR MASSIVE $e\nu\gamma$ AND $\mu\nu\gamma$ FINAL STATES AT THE CERN SUPER PROTON SYNCHROTRON COLLIDER

UA1 Collaboration, CERN, Geneva, Switzerland

Aachen¹-Annecy (LAPP)²-Birmingham³-CERN⁴-Helsinki⁵-Queen Mary College, London⁶-
Paris (Coll. de France)⁷-Riverside⁸-Rome⁹-Rutherford Appleton Lab.¹⁰-
Saclay (CEN)¹¹-Vienna¹² Collaboration

G. Arnison¹⁰, A. Astbury¹⁰, B. Aubert², C. Bacci⁹, G. Bauer*, A. Bézaguet⁴, R.K. Bock⁴,
T.J.V. Bowcock⁶, M. Calvetti⁴, P. Catz², P. Cennini⁴, S. Centro⁴, F. Ceradini^{4,9}, S. Cittolin⁴,
D. Cline*, C. Cochet¹¹, J. Colas², M. Corden³, D. Dallman^{4,12}, D. Dau**, M. DeBeer¹¹,
M. Della Negra^{2,4}, M. Demoulin⁴, D. Denegri¹¹, A. Di Ciaccio⁹, D. DiBitonto⁴, L. Dobrzynski⁷,
J.D. Dowell³, K. Eggert¹, E. Eisenhandler⁶, N. Ellis⁴, P. Erhard¹, H. Faissner¹, M. Fincke**,
G. Fontaine⁷, R. Frey⁸, R. Frühwirth¹², J. Garvey³, S. Geer⁺⁺, C. Ghesquière⁷, P. Ghez²,
K.L. Giboni¹, W.R. Gibson⁶, Y. Giraud-Héraud⁷, A. Givernaud¹¹, A. Gonidec², G. Grayer¹⁰,
T. Hansl-Kozanecka¹, W.J. Haynes¹⁰, L.O. Hertzberger***, C. Hodges⁸, D. Hoffmann¹,
H. Hoffmann⁴, D.J. Holthuisen***, R.J. Homer³, A. Honma⁶, W. Jank⁴, G. Jorat⁴, P.I.P. Kalmus⁶,
V. Karimäki⁵, R. Keeler⁶, I. Kenyon³, A. Kernan⁸, R. Kinnunen⁵, W. Kozanecki⁸, D. Kryn^{4,7},
F. Lacava⁹, J.-P. Laugier¹¹, J.-P. Lees², H. Lehmann¹, R. Leuchs¹, A. Lévêque^{11,4}, D. Linglin²,
E. Locci¹¹, J.-J. Malosse¹¹, T. Markiewicz⁴, G. Maurin⁴, T. McMahon³, J.-P. Mendiburu⁷,
M.-N. Minard², M. Mohammadi*, M. Moricca⁹, K. Morgan⁸, H. Muirhead⁴, F. Muller⁴,
A.K. Nandi¹⁰, L. Naumann⁴, A. Norton⁴, A. Orkin-Lecourtois⁷, L. Paoluzi⁹, F. Pauss⁴,
G. Piano Mortari⁹, E. Pietarinen⁵, M. Pimiä⁵, A. Placci⁴, J.P. Porte⁴, E. Radermacher¹, J. Ransdell⁸,
H. Reithler¹, J.-P. Revol⁴, J. Rich¹¹, M. Rijssenbeek⁴, C. Roberts¹⁰, J. Rohlf^{4,++}, P. Rossi⁴,
C. Rubbia⁴, B. Sadoulet⁴, G. Sajot⁷, G. Salvi⁶, G. Salvini⁹, J. Sass¹¹, J. Saudraix¹¹,
A. Savoy-Navarro¹¹, D. Schinzel⁴, W. Scott¹⁰, T.P. Shah¹⁰, D. Smith⁸, M. Spiro¹¹, J. Strauss¹²,
J. Streets³, K. Sumorok⁴, F. Szoncs¹², C. Tao***, G. Thompson⁶, J. Timmer⁴, E. Tscheslog¹,
J. Tuominiemi⁵, B. Van Eijk***, J.-P. Vialle⁴, J. Vrana⁷, V. Vuillemin⁴, H.D. Wahl¹², P. Watkins³,
J. Wilson³, R. Wilson⁺⁺, C.-E. Wulz¹², Y.G. Xie⁴, M. Yvert², E. Zurfluh⁴

(Submitted to Physics Letters B)

*) University of Wisconsin, Madison, Wisconsin, USA.

**) University of Kiel, Fed. Rep. Germany.

***) NIKHEF, Amsterdam, The Netherlands.

+) Visitor from the University of Liverpool, England.

++) Harvard University, Cambridge, Mass., USA.

ABSTRACT

The observation of an apparent excess of radiative Z^0 decays into $e^+e^-\gamma$ and $\mu^+\mu^-\gamma$ has prompted the search for massive $e\nu\gamma$ and $\mu\nu\gamma$ final states containing an energetic photon. No events were found other than those consistent with QED radiative effects in leptonic W decays. The data sample corresponds to an integrated luminosity of 0.136 pb^{-1} produced at the CERN Super Proton Synchrotron (SPS) Collider. An upper limit on the occurrence of such events is given.

1. INTRODUCTION

We have recently reported the observation of four $Z^0 \rightarrow e^+e^-$ events [1]. In one of these events, the momentum measurement by curvature of the negative track showed a value of (9 ± 1) GeV/c, much smaller than the corresponding calorimeter deposition of (48 ± 1) GeV. We interpreted this event as the likely emission of a hard “photon” [2] accompanying the electron. Subsequent calibrations of the electromagnetic (e.m.) counters indicated that the centroid of the energy deposition in the calorimeters was significantly displaced with respect to the incident electron track, indicating an angle of $\Delta\phi = (14 \pm 4)$ degrees between the charged and neutral components. This made the possibility of an external bremsstrahlung in the vacuum pipe and detector window seem unlikely. The estimated probability of an internal bremsstrahlung exceeding the angle and energy observed is, according to Berends [3], about 0.005, or 2% for the sample of four events.

A rather similar event has been reported by the UA2 Collaboration [4]. In this case the photon and electron hit separate cells, thus directly indicating a finite $e-\gamma$ separation. Characteristics of these two events are given in Table 1. More recently, an event of the type $\mu^+\mu^-\gamma$ has been observed in our study of $Z^0 \rightarrow \mu^+\mu^-$ decays [5]. Also in this event, a small but finite angle ($\sim 8^\circ$) is observed between the muon and the hard photon ($E \sim 30$ GeV).

It is certainly premature to draw any conclusion about the origin of such events. The present paper deals with a search for an analogous phenomenon in the charged Intermediate Vector Boson channels, namely for processes leading to final states of the type $e\nu\gamma$ and $\mu\nu\gamma$, where γ is a hard photon of transverse energy E_T in excess of 10 GeV.

The UA1 detector has been designed to study the large-angle phenomenology of $p\bar{p}$ collisions at $\sqrt{s} = 540$ GeV. The apparatus and the data-taking conditions are essentially unchanged from those previously reported, and we refer the reader to ref. 1 for more details. The main features of the UA1 detector that are relevant for the present investigation are i) electron detection, ii) neutrino detection, iii) momentum analysis of charged particles, and iv) muon detection. Details of the features (i) to (iii) of the UA1 detector can be found in ref. 6, and (iv) can be found in ref. 1.

2. EVENT SELECTION

The event selection follows very closely the one used in our previous analysis to search for ordinary $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ decays, except that the procedure has been modified so as not to exclude the radiative events on the basis of track isolation or event topology.

2.1 Search for $e\nu\gamma$ events

Results are based on an integrated luminosity of 0.136 pb^{-1} , which is corrected for dead-time and similar losses. This exposure resulted in the sample of 52 charged intermediate vector boson decays in the $(\nu_e e)$ channel previously reported [6]. The trigger selection required the presence of an e.m. cluster at angles larger than 5° with respect to the beam direction, and with transverse energy in excess of 10 GeV. After on-line filtering and complete off-line reconstruction, about 1.5×10^5 events had at least one e.m. cluster (two adjacent e.m. calorimeter cells) with $E_T > 15$ GeV.

To search for the process $W^\pm \rightarrow e^\pm \nu_e \gamma$, events have been required to survive at least one of two complementary sets of cuts:

- i) Missing-energy selection: In the hermetic UA1 detector an energetic neutrino manifests itself as a transverse energy imbalance. We require a transverse energy imbalance that is in excess of

15 GeV and, in order to ensure the best accuracy, the missing energy vector must not point vertically ($\pm 20^\circ$). Finally we impose a topology cut [7] to remove spurious background associated with two-jet events. After this selection we are left with 199 candidates for further analysis.

- ii) Charged-particle selection: In addition to an e.m. cluster with $E_T > 15$ GeV, we require the presence of an associated, isolated [6] track with $p_T > 7$ GeV/c in the central detector (CD), less than 600 MeV deposited in the hadron calorimeter cells immediately behind the electromagnetic cluster, less than 3 GeV transverse energy deposited in the hadron calorimeter within a larger specified [8] cone, and a missing transverse energy in excess of 10 GeV. No further cut on the topology of the event has been made. We are left with the 52 published $W^\pm \rightarrow e^\pm \nu_e$ decays, plus an additional 27 events for further analysis.

2.2 Search for $\mu\nu\gamma$ events

Results are based on an integrated luminosity of 0.111 pb^{-1} , which is corrected for dead-time and similar losses. The trigger selection required the presence of at least one penetrating track detected in the UA1 muon chambers with pseudorapidity $|\eta| \leq 1.3$, and pointing in both projections to the interaction vertex within a specified cone of aperture ± 150 mrad.

After off-line reconstruction we require a charged track in the CD with $p_T > 15$ GeV/c, or $p > 30$ GeV/c, which matches, in both projections, the reconstructed track in the muon chambers. Cosmic rays and muons from identified meson decays are removed, leaving a sample of 144 high- p_T muon events for further examination.

3. RESULTS

The three event samples have been examined by physicists on Megatek, the visual scanning and interactive facility. Requiring the photon to have a transverse energy in excess of 10 GeV and the lepton to be isolated, no events that are consistent with the production and decay of a massive ($e^\pm \nu_e \gamma$) or ($\mu^\pm \nu_\mu \gamma$) state have been found. Amongst the events of the electron samples are the 52 $W^\pm \rightarrow e^\pm \nu_e$ decays previously reported. Amongst the surviving muon candidate events we have obtained a preliminary sample of 18 $W^\pm \rightarrow \mu^\pm \nu_\mu$ candidates [5]. There is no evidence for an additional photon with transverse energy in excess of 10 GeV in these events. Furthermore, the energy deposited by the muon in the e.m. calorimeters is consistent with that expected from radiative and ionization losses, together with the contribution from the minimum-bias background (figs. 1 and 2).

To consolidate these results, the UA1 jet algorithm [9] has been used to search for energetic photons in the three event samples [10]. Once again, after requiring the lepton to lie outside of a hadronic jet, we find no evidence for an energetic photon in any of the events.

4. CONCLUSIONS

We have found no evidence for events of the type $e\nu\gamma$ or $\mu\nu\gamma$ where the e.m. neutral particle or cluster (γ , π^0 , or η) has a transverse energy in excess of 10 GeV. Therefore, the radiative effect observed in the Z^0 candidates is not present in the much larger sample of W decays.

We can also calculate an upper limit for R , the fraction of leptonic W decays which are accompanied by an energetic photon, provided we adopt a model of the decay kinematics of the process. Our evaluation is based on the electron samples. This enables us to use our published sample of 52 $W \rightarrow e\nu$ decays in the calculation of the limit on R .

i) Three-body phase space:

$$R \equiv \text{BR}(W^\pm \rightarrow \ell^\pm \nu_\ell \gamma) / \text{BR}(W^\pm \rightarrow \ell^\pm \nu_\ell).$$

Allowing for selection efficiency and geometrical acceptance, we find that $R \leq 0.1$ (90% confidence level).

ii) Production of an excited state of the charged lepton:

$$W^\pm \rightarrow \ell^* \nu_\ell (\ell^* \rightarrow \ell^\pm \gamma).$$

Then $R \equiv \text{BR}(W^\pm \rightarrow \ell^* \nu_\ell \rightarrow \ell^\pm \gamma \nu_\ell) / \text{BR}(W^\pm \rightarrow \ell^\pm \nu_\ell)$, and the experimental sensitivity depends upon the mass of the excited spin $1/2$ leptonic state ℓ^* . In fig. 3a the result is shown as a function of this mass. In the mass range $10 \text{ GeV}/c^2 \leq m_{\ell^*} \leq 70 \text{ GeV}/c^2$ we place an upper limit on R falling from 0.2 at low masses to 0.1 at high masses (90% confidence level).

iii) Radiative decay of a heavy W into a lighter W :

$$\bar{W} \rightarrow W \gamma (W \rightarrow \ell \nu_\ell).$$

and

$$W \rightarrow \bar{W} \gamma (\bar{W} \rightarrow \ell \nu_\ell).$$

Then $R \equiv (\sigma \cdot \text{BR})_{\bar{W}} / (\sigma \cdot \text{BR})_W$. An upper limit on R depends upon the masses of the $\bar{W}$ and the W , and their spin assignments. Fixing the W mass at the measured value [6] and varying both the $\bar{W}$ mass and the spin assignments, the results are shown in fig. 3b. Outside the region where the $\bar{W}$ mass is within $10 \text{ GeV}/c^2$ of the W mass we put an upper limit on R . This varies from 0.2 at low $\bar{W}$ masses ($\gtrsim 30 \text{ GeV}/c^2$) to 0.1 at high $\bar{W}$ masses (90% confidence level).

Finally, we remark that the e^+e^- invariant mass of both events in Table 1 is in the interval $40\text{--}50 \text{ GeV}/c^2$. An inclusive search for additional e^+e^- pairs in this mass range has also given a negative result.

Acknowledgements

The continued success of the Collider and the steady increase in luminosity which has made this result possible depend critically upon the superlative performance of the whole CERN accelerator complex, which was magnificently operated by its staff. We thank W. Kienzle who, as coordinator, balanced very effectively the sometimes conflicting interests of the physicists and accelerator staff. We have received enthusiastic support from the Director General, H. Schopper, and his Directorate, for the results emerging from the SPS Collider programme.

We are thankful to the management and staff of CERN and of all participating Institutes who have vigorously supported the experiment.

The following funding Agencies have contributed to this programme:

Fonds zur Förderung der Wissenschaftlichen Forschung, Austria.

Valtion luonnontieteellinen toimikunta, Finland.

Institut National de Physique Nucléaire et de Physique des Particules and

Institut de Recherche Fondamentale (CEA), France.

Bundesministerium für Forschung und Technologie, Germany.

Istituto Nazionale di Fisica Nucleare, Italy.

Science and Engineering Research Council, United Kingdom.

Department of Energy, USA.

Thanks are also due to the following people who have worked with the Collaboration in the preparation of and data collection on the runs described here: O.C. Allkofer, F. Bernasconi, F. Cataneo, R. Del Fabbro, L. Dumps, D. Gregel and G. Stefanini.

REFERENCES AND FOOTNOTES

- [1] G. Arnison et al. (UA1 Collaboration), Phys. Lett. **126B** (1983) 398.
- [2] We define a "photon" candidate as a transverse energy deposition in excess of 10 GeV in two adjacent e.m. calorimeter cells, with no associated charged tracks with transverse momentum in excess of 1 GeV/c, and less than 600 MeV energy deposited in the hadronic calorimeter cells immediately behind the e.m. cluster. In addition, we require that this cluster is not part of a larger calorimeter jet structure as defined by the UA1 jet algorithm (see ref. 9).
- [3] F. Berends et al., Nucl. Phys. **B202** (1982) 63, and private communications.
- [4] P. Bagnaia et al. (UA2 Collaboration), Phys. Lett. **129 B** (1983) 130.
- [5] G. Arnison et al. (UA1 Collaboration), in preparation.
- [6] G. Arnison et al. (UA1 Collaboration), Phys. Lett. **122B** (1983) 103.
G. Arnison et al. (UA1 Collaboration), Phys. Lett. **129B** (1983) 273.
- [7] Events having two coplanar ($\pm 30^\circ$) calorimeter clusters with $E_T > 15$ GeV are excluded if the missing transverse energy vector is in the direction ($\pm 20^\circ$) of one of the clusters. A genuine $e\nu\gamma$ event having this topology would be recovered by the high- p_T track selection.
- [8] A cone in (rapidity, azimuthal angle) space was used, centred on the high- p_T track, and described by the expression $(\eta^2 + \phi^2)^{1/2} < 0.7$, where η is in units of rapidity and ϕ is in radians.
- [9] G. Arnison et al. (UA1 Collaboration), preprint CERN-EP/83-118 (1983), submitted to Physics Letters B.
G. Arnison et al. (UA1 Collaboration), preprint CERN-EP/83-119 (1983), submitted to Physics Letters B.
- [10] In the search for a photon using the UA1 jet algorithm, a photon candidate was defined as a calorimeter cluster in which i) there is no associated CD jet, and ii) there are two adjacent e.m. cells having between them $E_T > 10$ GeV and 80% of the cluster energy. All events from samples (1) to (3) having such a "photon candidate" were found, on closer inspection, to be two-jet events.

Table 1

Energy, angle, and mass properties of the $ee\gamma$ events

	UA1	UA2
E_γ (GeV)	38.8 ± 1.5	24.4 ± 1.4
E_{e_1} (GeV)	61.0 ± 1.2	68.5 ± 1.6
E_{e_2} (GeV)	9 ± 1	11.4 ± 0.9
$\Delta\phi(e_2\gamma)$ ($^\circ$)	14.4 ± 4.0	31.8
$m(e_1e_2)$ (GeV/ c^2)	42.7 ± 2.4	49.8
$m(e_1e_2\gamma)$ (GeV/ c^2)	98.7 ± 5.0	89.7 ± 2.8
$m(e_1\gamma)$ (GeV/ c^2)	88.8 ± 2.5	74.1
$m(e_2\gamma)$ (GeV/ c^2)	4.6 ± 1.0	9.1

Notes: For the UA1 event $e_1 = e^+$ and $e_2 = e^-$.

The UA2 numbers are calculated from ref. [4].

Figure captions

- Fig. 1: Energy deposited by the muon in the e.m. calorimeters for a preliminary sample of 20 $W^\pm \rightarrow \mu^\pm \gamma_\mu$ candidates. The data are consistent with the curve, which is a prediction including radiative [3] plus ionization losses, and a contribution from the minimum-bias background.
- Fig. 2: The same as figure 1 for the four longitudinal samplings of the electromagnetic shower calorimeter.
- Fig. 3: Upper limit (90% c.l.) for R , the fraction of leptonic W decays accompanied by a photon with transverse energy in excess of 10 GeV. The electron samples have been used to extract the limits on R , which are model-dependent. Results are shown for the following two models:
a) the process $W \rightarrow e^* \nu_e (e^* \rightarrow e \gamma)$ with $m_W = 80.9 \text{ GeV}/c^2$ [6], and
b) $\bar{W} \rightarrow W \gamma (W \rightarrow e \nu_e)$, where one of the boson masses has been taken to be $80.9 \text{ GeV}/c^2$, and the shaded band shows the dependence of the limit on the bosons spin assignments (0 or 1).

Fig. 1

Fig. 2

Fig. 3a

Fig. 3b