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Search for Monojet Production in e^+e^- annihilation

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We report results of a search for events of the type $e^+e^- \rightarrow$ jet + missing transverse momentum using the Mark II detector at PEP. Two candidate events were found, but both could come from known sources of background. A specific model for the origin of UA1 monojet events as the decay of a Z boson into two light Higgs bosons is eliminated by this search.

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Arnison *et al.* (UA1 Collaboration) studying $p\bar{p}$ collisions at the CERN SPS Collider have reported five events in which a missing transverse energy of greater than 40 GeV is associated with a narrow hadronic jet, and for which there is no conventional explanation.[1] The invariant mass of the system of the jet and the missing energy in four of the five events is consistent with the mass of the Z boson.[2] Thus, one possible hypothesis is that at least some of these events are caused by a two-body Z decay in which one of the particles escapes the detector without interacting and the other decays to a hadronic jet.[3] Models of this type[4,5] can be tested at present-energy e^+e^- storage rings provided that the masses of the Z decay products are sufficiently small. In this Letter we report a search for the process $e^+e^- \rightarrow$ jet + missing transverse momentum that is sufficiently sensitive to have implications for the origin of the UA1 monojet events.

The data for this search were collected with the Mark II detector at the Stanford Linear Accelerator Center e^+e^- storage ring PEP at a center-of-mass energy of 29 GeV. This analysis is based on an integrated luminosity of 222 pb^{-1}, corresponding to the production of approximately 90 000 hadronic events.

The Mark II detector has been described in detail elsewhere.[6] Here we briefly describe those elements of the detector that are relevant to this analysis. A high-precision drift chamber, known as the vertex chamber, surrounds the beam pipe.[7] The vertex chamber contains four inner cylindrical bands of sense wires at an average radii of 11.2 cm and three outer cylindrical bands of sense wires at an average radius of 31.2 cm. The half-length of the chamber is 60 cm and, thus, charged particles can be detected to within 12° of the beam axis. The main drift chamber surrounds the vertex chamber. The drift chamber contains sixteen cylindrical layers of wires at radii between 41 and 145 cm, and can track charged particles at angles of greater than 37° to the beam axis. Both tracking chambers are located in an axial magnetic field of 2.3 kG. 48 axial scintillation counters surround the drift chamber at a radius of 1.5 m and are sensitive in the region $|\cos\theta| < 0.75$, where θ is the angle-to-beam axis.

Photons are detected by three different electromagnetic calorimeters. The central region contains eight lead–liquid-argon calorimeter modules.[8] These 14-radiation-length counters surround the solenoidal coil and have an approximate acceptance of $|\cos\theta| < 0.70$. However, about 6% of the azimuth is uninstrumented because of gaps between the modules. End-cap shower counters of 5-radiation-length thickness cover the angular region $0.75 < |\cos\theta| < 0.92$, but a large gap exists in the aximuthal coverage because of the presence of a support stand. These end-cap counters are composed of lead sheets and wire chambers. Finally, the forward and backward angular regions between 21 and 82 mrad are covered by 15-radiation-length lead-scintillator calorimeters, known as the small-angle tagger.[9]

For each event a missing momentum, $\bar{\mathbf{p}}$, was calculated as the negative of the sum of the momenta of all of the detected charged and neutral particles in the event. The projection of this momentum into the plane perpendicular to the beam is denoted by $\bar{\mathbf{p}}_\perp$. Each candidate event was required to have (1) at least two charged particles originating near the interaction region, each of which had momentum greater than 300 MeV/c and $|\cos\theta| < 0.7$; (2) $\bar{\mathbf{p}}_\perp > 8$ GeV/c; (3) $|\cos\theta_{\bar{\mathbf{p}}}| < 0.67$; (4) for every detected charged and neutral[10] particle with momentum $\mathbf{p}$, $\mathbf{p}\cdot\bar{\mathbf{p}} < 0$, and $\mathbf{p}\cdot\bar{\mathbf{p}}_\perp < 0$; and (5) $\bar{\mathbf{p}}_\perp$ not point to within 2.25° of the center of a gap between calorimeter modules. Requirements (3) and (5) were designed to eliminate as much as possible events in which the missing momentum was contained in a single undetected photon.

41 events met all of the above requirements. A hand scan of these events was done to eliminate those in which there was evidence of an undetected particle in the direction of $\bar{\mathbf{p}}$. Two events were eliminated because there was an untracked particle in the vertex or drift chamber.

Twenty events were eliminated because a scintillation counter within 10° of $\bar{\mathbf{p}}_\perp$ fired. These counters can be hit by backward-going particles from an electromagnetic shower. A study of isolated high-energy photon showers indicates that a scintillation counter is hit in front of a shower 69% of the time. In the events discussed here, a counter firing is a strong indication of the existence of an otherwise undetected photon, because it showers either in a gap between the central calorimeter modules or in the gap in polar-angle coverage between the central and end-cap shower counters.

Seven events were eliminated because there was evidence of an electromagnetic shower in the direction of $\bar{\mathbf{p}}_\perp$ that was undetected by the analysis programs, either because it developed along the edge of a module or because it developed only in the back half of the calorimeter. And, finally, a single event was eliminated because there was clear evidence of the failure of the calorimeter system on that event.

Of the eleven remaining events, nine contained only two electrons. These events are consistent with coming from the processes $e^+e^- \rightarrow e^+e^-\gamma$ and $e^+e^- \rightarrow e^+e^-\gamma\gamma$ in which all the photons are undetected. Since the present search is for hadronic jets, these events are not considered further here.

Two events remain as monojet candidates. One has three charged particles and two photons which make up a jet of mass 1.2 GeV/c^2, with $\bar{\mathbf{p}}_\perp = 9.6$ GeV/c. This event could be a radiative τ pair in which one τ decays to a low-energy lepton that is swept into the forward region and not detected. The second event contains a jet with nine charged particles and six photons which make up a jet of mass 5.7 GeV/c^2, with $\bar{\mathbf{p}}_\perp = 12.7$ GeV/c^2. This event is consistent with being a radiative hadronic event in which the photon is undetected in a gap between the calorimeter modules. In this event $\bar{\mathbf{p}}_\perp$ pointed 2.9° away from the center of a gap between calorimeter modules, just passing the cut at 2.25°. The typical resolution in the direction of $\bar{\mathbf{p}}_\perp$ is 1.6° in events of this complexity. A study of radiative hadronic events indicates that two background events could be expected from this process.

Although these two events are likely to come from known sources of background, they are also consistent with being the signal for which we are searching. Thus, we will consider them as possible signal events in the analysis which follows.

To assess the significance of this search, it is necessary to use a specific model. The model of Glashow and Manohar[4] assumes two Higgs doublets which produce five physical Higgs bosons. Three of these, one neutral and two charged, are heavy, and two, both neutral, are light: a scalar, which we will call S, and a pseudoscalar, which we will call P. The monojet events observed by Arnison *et al.* are thus posited to be from decays of the form $Z \rightarrow SP$, where the S is very light and, hence, has a long lifetime which allows it to escape the detector before decaying. The heavier P decays rapidly to massive fermion pairs, such as $c\bar{c}$ and $\tau^+\tau^-$, appearing as a hadronic jet in the detector. The branching fraction for $Z \rightarrow SP$ is predicted to be approximately the same as that for $Z \rightarrow e^+e^-$ or $Z \rightarrow \mu^+\mu^-$,[11] in good agreement with the number of events observed by Arnison *et al.*

Virtual Z decays may be observed at present e^+e^- storage ring energies. The only differences between virtual and real Z decays are due to kinematic effects. The partial width for virtual Z decay into two spin-0 bosons contains a threshold factor $f = (2|\mathbf{p}_E|/E)^3$, where $\mathbf{p}_E$ is the momentum of one of the bosons at center-of-mass energy E.[12] Thus, the differential cross section for $Z \rightarrow SP$ is[12,13]

$$\frac{d\sigma}{d\Omega} = f\frac{G_F^2E^2}{256\pi^2} \times \left(\frac{(1-4\sin^2\theta_W)^2+1}{(1-E^2/m_Z^2)^2+\Gamma_Z^2/m_Z^2}\right)\sin^2\theta. \quad (1)$$

For an integrated luminosity of 222 pb^{-1} and $f = 1$, Eq. (1) implies that 41 events would be produced.

To determine the detection efficiency, Monte Carlo simulations were performed for different values of m_P and for two assumptions for m_S, that (a) $m_S = 0$ and (b) $m_S = m_P$, although only a very light m_S, which allows S to escape the detector before decaying, conforms to the specific model of Ref. 4. The P boson was assumed to decay to heavy quark and lepton pairs in proportion to $m_f^2\beta_f$, where m_f and β_f are the mass and velocity of each fermion, respectively.[14] For a jet to qualify as a P boson of a given mass m, the observed jet mass was required to lie between $0.5m$ and $1.1m$. The maximum efficiency for hadronic decays was about 36%, which occurred for the case of $m_P = 5$ GeV/c^2. The efficiency for P decays to $\tau^+\tau^-$ was about half that for hadronic decays. The reduced efficiency for $\tau^+\tau^-$ was largely caused by the apparent smaller $\bar{\mathbf{p}}_\perp$ due to the existence of at least two neutrinos in each event. The reduction in efficiency for $m_P < 5$ GeV/c^2 is due to a software trigger early in the Mark II analysis chain. The efficiency calculation includes a -5% electromagnetic radiative correction.[15]

The two possible signal events had nonoverlapping

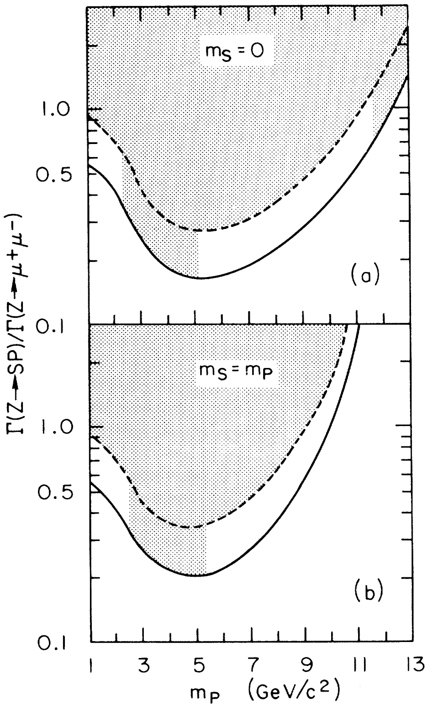

FIG. 1. Upper limits on the ratio of rates for $Z \to SP$ to $Z \to \mu^+\mu^-$, under the assumption that S decays outside the detector and P decays to heavy quark and lepton pairs for (a) $m_S = 0$ and (b) $m_S = m_P$. The solid and dashed lines represent the 90%-confidence limits for 0 and 1 events observed, respectively. The shaded area represents the excluded region. The model of Ref. 4 predicts a value of 1.0 in (a) independent of m_P.

jet masses. Thus, for each possible m_P, either zero or one possible event was observed. Figure 1 shows the 90%-confidence-level upper limits on the ratio of the partial widths for $Z \to SP$ to $Z \to \mu^+\mu^-$, under the assumption that S decays outside the detector. The model of Ref. 4 [Eq. (1)] and the rate of production of monojet events in the UA1 experiment, if they are to be ascribed to this process, both predict this ratio to be about unity. This level of production would imply the observation of fourteen events in this experiment for $m_P = 5$ GeV/c^2 and at least four events for $m_P < 11$ GeV/c^2. Thus, it appears that this mechanism, with $m_P < 11$ GeV/c^2, cannot be the main source of the monojet events observed by the UA1 experiment.

After the completion of this analysis we received a report from the high-resolution spectrometer (HRS) experiment at PEP of a similar search with similar conclusions.[16]

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[3] New preliminary data from the UA1 experiment [J. Rohlf, in Proceedings of the Conference on New Phenomena at the SPS Collider: Implications for SSC and Beyond, Berkeley, California, 18–19 January 1985 (unpublished)] yield four new monojet events with missing transverse energy greater than 40 GeV, three of which appear consistent with the Z mass. There are also four dijet jet events with missing transverse energy greater than 40 GeV and with masses larger than the Z mass. These latter events could not be caused by the process discussed in this Letter.

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[10] For this purpose a neutral particle is defined as a deposit of the shower equivalent of 150 MeV of energy in one of the calorimeters at a distance greater than 30 cm from the projection of the closest charged track.

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[12] See, for example, F. M. Renard, *Basics of Electron Positron Collisions* (Editions Frontières, Dreux, 1981).

[13] Note that the cross section is not sensitive to precise values of m_Z, Γ_Z, or $\sin^2\theta_W$.

[14] The kinematic factor is β_f because P is assumed to be a pseudoscalar. If P were a scalar, the kinematic factor would change to β_f^3, but this would not significantly affect the results.

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