EXPERIMENTAL LIMITS ON MONOJET PRODUCTION IN e^+e^- ANNIHILATION AT 29 GeV

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A search was made for $e^+e^- \to X_1X_2$ where X_1 consists of one or more light unobservable particles and X_2 decays promptly to a visible jet of particles One event was found for an integrated luminosity of 176 pb^{-1}, a rate consistent with known backgrounds. This result places a significant constraint on a number of theoretical models

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The existence of neutrinos was first inferred from the observation of particle interactions which appeared to violate the conservation of momentum and energy. The question arises if other neutral, weakly interacting particles exist which might yield a similar experimental signature. Indeed, a number of theoretical models have postulated such particles. This question has received intense interest following the recent observation in the CERN UA1 experiment of events containing jets of particles with very large transverse momentum not balanced by any other visible particles [1]. Several ideas have been suggested to explain these monojet events. They include the production of supersymmetric particles [2], bound states of gauge bosons [3], and anomalous decays of the Z^0 boson [4,5]. Such phenomena all lie outside the domain of the standard model. It is therefore important to search for such events in other experimental situations.

We report results from a search for monojets with the high resolution spectrometer (HRS) at the PEP e^+e^- storage ring. The search was conducted at a CM energy of 29 GeV with an integrated luminosity of 176 pb^{-1}. Monojets are defined here as events with energetic clusters of particles all of which are contained within one hemisphere and for which the net momentum vector is at large angles with respect to the beams. Such events exhibit large unbalanced momentum and missing energy.

The HRS detector has been described in detail elsewhere [6]. Charged particles are tracked over 90% of the full solid angle in a 1.6 T magnetic field, and photons are detected with a lead-scintillator calorimeter. The calorimeter consists of a barrel which surrounds the region $|\cos\theta| < 0.60$ and two end caps which cover $0.70 < |\cos\theta| < 0.94$, where θ is the angle with respect to the positron beam direction. The gaps between the barrel and end caps are partially covered with lead and proportional wire chambers (PWC's) leaving two insensitive regions each of which is 2.0° wide. The barrel calorimeter is segmented azimuthally into 40 modules whereas each end cap is divided into 20 sections. Showers are located with an accuracy of ±2 cm by the PWC system.

Events were selected according to the following criteria:

(1) Charged multiplicity $4 \leqslant n_c \leqslant 10$.

(2) Total visible energy of charged particles and neutrals greater than 8.0 GeV.

(3) $|\boldsymbol{p}_c| = |\Sigma \boldsymbol{p}_i| > 4.83$ GeV/c where $\boldsymbol{p}_c$ is the sum of the charged particle momenta $\boldsymbol{p}_i$. The value 4.83 GeV/c is equal to one third of the beam momentum.

(4) $|\cos\theta_c| < 0.5$ where θ_c is the angle between $\boldsymbol{p}_c$ and the positron beam direction.

(5) No charged particles in the hemisphere opposite $\boldsymbol{p}_c$.

(6) No signal in the calorimeter in the hemisphere opposite $\boldsymbol{p}_c$.

Two events were found to satisfy these criteria. They are shown in fig. 1 and described in table 1.

The dominant source of potential background for this search consists of events with initial-state radiation of a high-energy photon at large angles and the annihilation of the remaining electron–positron system into hadrons. In many of these events the hadrons form a low-mass cluster which has the appearance of a single jet in the direction opposite to the photon. If the photon enters the insensitive 2° gaps between the end-cap and barrel calorimeters or does not convert in the structural material separating the barrel calorimeter modules, then such events will be misidentified as monojets.

To estimate this background we have studied events with initial-state radiation using selection criteria (1)–(5) above, but replacing condition (6) with the requirement of a calorimeter signal consistent with a single photon opposite to the hadronic jet. This selection yielded 166 events. We refer to these as photon–jet events. The acollinearity distribution in polar angle θ between detected photons and the net momentum of the charged particles is shown in fig. 2. The width of this distribution was used to determine the requirement $|\cos\theta_c| < 0.5$ which forces the jet axis to be at least 10° away from the gaps between the barrel and end-cap calorimeters. Approximately 7% of events with a photon in these 2° gaps will satisfy this requirement, yielding a background to the monojet event sample of 0.7 ± 0.2 events from this source.

Photon–jet events also contribute a background if the photon enters the region between barrel calorimeter modules and does not convert in the front section of the mechanical structure separating the scintillators. The probability, averaged over the whole barrel calorimeter, for a photon to miss detection was determined from a study of radiative, acollinear Bhabha and μ-pair events. The electron and muon tracks were used to determine a missing recoil mass and momen-

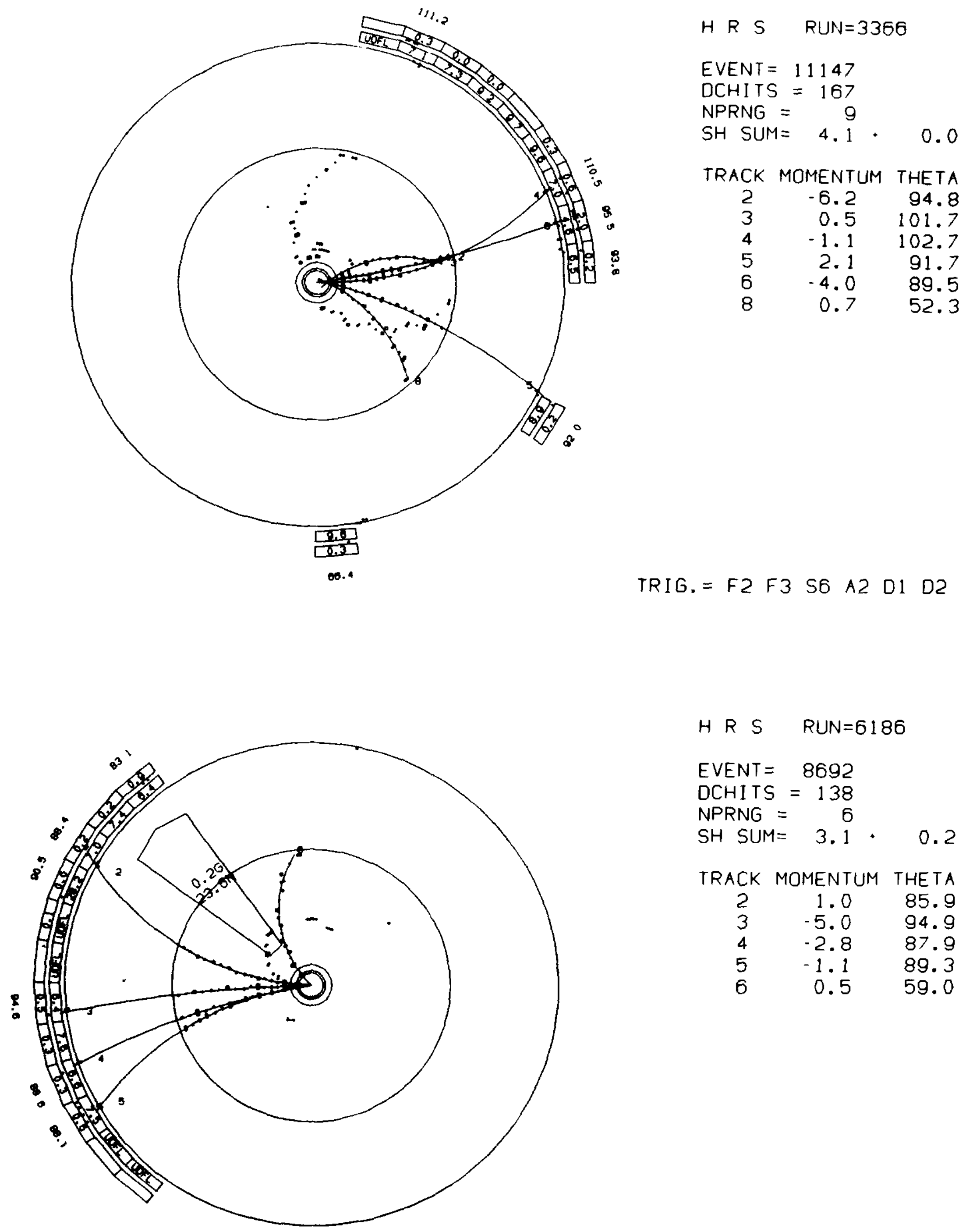

Fig. 1. Display of events satisfying the selection criteria for monojets. Tracks and calorimeter signals are indicated in this transverse view of the HRS.

Table 1
Events satisfying selection requirements for monojets.

Run	Event	n_c	$\cos\theta_c$	Visible jet energy (GeV)			Jet mass (GeV/c^2)
				charged	neutral	total	
3366	11147	6	−0.05	>10 6	>0 3	>10 9	>3.8
6186	8692	6	0.00	10 5	1.7	12.2	>3 6

tum. The missing mass was required to be near zero as expected for photons and the missing momentum was required to point well into the barrel calorimeter and have a magnitude greater than 3.0 GeV/c. A sample of 255 such events included four with no visible photon, yielding a measured inefficiency of (1.6 ± 0.8)%. This value is consistent with an estimate of 1.4% based on the calorimeter design and on general properties of showers. Combining this inefficiency with the number of observed photon–jet events yields an additional background for monojets of 2.6 ± 1.3 events.

The overall background to monojets from initial-state radiation is therefore expected to be 3.3 ± 1.5 events. Other potential sources of background involving two-photon processes or annihilation events with undetected neutral particles have been investigated and found to be small. We have also checked that photons were not missed in the selected events because of detector failures.

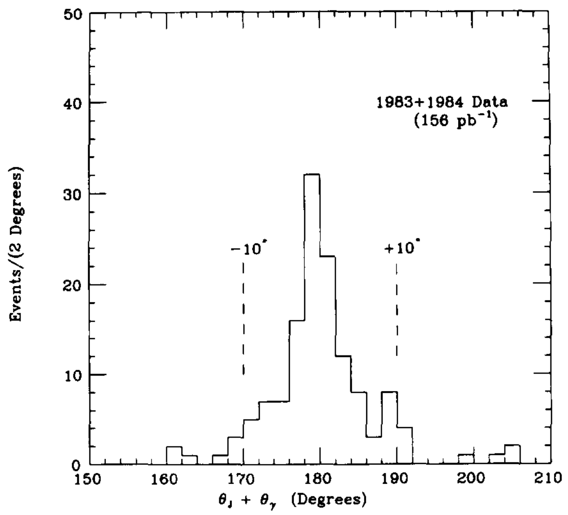

Fig. 2. Distribution of the sum of photon and jet polar angles in events with initial-state radiation.

As noted above we have observed two events with monojets. The event from run 6186 is consistent with the background from initial-state radiation given the uncertainty in the estimated background rate. The other event (run 3366) exhibits an additional anomaly in that all charged tracks (with the possible exception of one) originate at a point 7.7 ± 0.2 cm distant from the beam line. The location of the event vertex is consistent within tracking errors with the 7.6 cm radius of the beam pipe. This pipe has a 1.4 mm thick beryllium wall whose interior is covered with a 0.05 mm thick titanium foil. Possible background processes for this event include $e^+e^- \to \gamma\gamma$ or $e^+e^- \to \gamma\pi^+\pi^-$ where a photon is undetected because of the inefficiences described above and where the other photon or a pion interacts hadronically in the beam pipe. We exclude this event from consideration when setting limits on monojet production from prompt particle decays.

We present upper limits for prompt monojet production using the result that we have observed no events with monojet masses below 3.6 GeV/c^2 and at most one possible candicate at higher masses. To estimate detection efficiencies, we consider the distinct possibilities that monojets arise from the production of either scalar particles or fermions. For the scalar case, detection efficiencies were calculated with the LUND Monte Carlo program [7] for the process $e^+e^- \to X_1X_2$ where X_1 is a light unobserved particle and where X_2 is a short-lived, massive particle whose visible decay products yield the monojet. We assumed that X_1 and X_2 are produced with a $\sin^2\theta$ distribution and that X_2 is a Higgs-like scalar which decays isotropically into strange quarks for masses below 4.5 GeV/c^2 or into charm quarks above 4.5 GeV/c^2. As the mass of X_2 increases the probability to satisfy the requirement of at least 4 charged tracks increases while the probability that no decay fragments go into the opposite (backward) hemisphere decreases. These competing factors yield a peak acceptance for X_2 masses around 5 GeV/c^2. Fig. 3 shows detection efficiencies as well as 90% CL upper limits for the production cross section of hadronically decaying scalar particles as a function of their mass. These limits vary from 0.05 to 0.12 pb over the mass range 2–10 GeV/c^2.

The production of scalar particles in e^+e^- annihilation through an intermediate Z^0 state is predicted to be about 0.18 pb at 29 GeV [4]. If the massive particle X_2 is a Higgs scalar, then the purely leptonic decay modes are expected to account for 30% or less of all decays. The cross section for hadronic monojets is thus expected to be 0.13 pb with some decrease as the mass of X_2 increases because of threshold factors as indicated in fig. 3. Our data exclude such a process for X_2 masses in the range from 2 to about 9 GeV/c^2 with a confidence level of 90% or higher. It is therefore unlikely that most of the CERN monojet events can be explained by the production of Z^0 bosons with their subsequent decay to scalar particles.

Monojets could also arise from Z^0-mediated pair production of heavy neutral leptons if one of the leptons decays entirely to light neutrinos [5]. In this case the production angular distribution is $(1 + \cos^2\theta)$ neglecting asymmetry terms. Our detection efficiency for such events is approximately a factor of 1.7 lower than for events with scalar particles. The cross section for the production of a massive neutrino pair, assuming standard couplings to the Z^0, is 0.36 pb. Our data place a 90% CL lower limit on the decay branching fraction to light neutrinos of 13 to 50% as the lepton mass increases from 2 to 10 GeV/c^2.

To investigate the impact of our result on supersymmetric models, we have made a comparison with one specific class of models. We assume that the lowest mass supersymmetric fermion, X_1 is a massless photino. The second lightest, X_2, will then be, in general, a mixture of supersymmetric Z^0 and Higgs particles. If we denote the zino fraction by λ^2, then the cross section for $e^+e^- \to X_1X_2$ via scalar electron exchange is given by [8]

$$\sigma = 0.61\,(1 - R)^2\,(1 + R/2)\,\lambda^2/r^4 \text{ (pb)},$$

where r is the ratio of scalar electron to W-boson mass, and $R = m^2/s$ is the square of the ratio of X_2 mass to CM energy. The angular distribution is expected to be $(1 + R) + (1 - R)\cos^2\theta$ where θ is the angle between the photino and beam directions. The possible decay modes of X_2 are (a) lepton pairs and photino, (b) quark pairs and gluino and (c) quark pairs and photino. This search is not sensitive to (a). The cross section limits for (b), assuming a prompt decay of the gluino have a dependence on the mass of X_2 which is similar to that for scalar particles but are higher by a factor of about 1.7 because of the different production angular distribution. If the gluino mass is larger than a few GeV/c^2

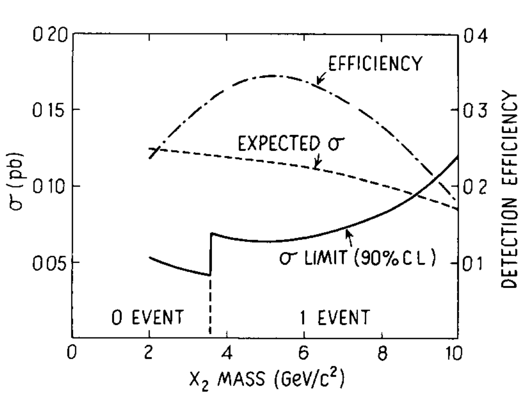

Fig. 3. Detection efficiencies, expected cross sections, and 90% CL cross section limits for prompt, hadronic monojets from the production and decay of scalar particles.

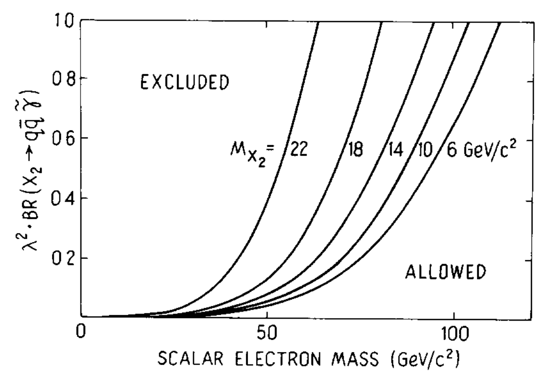

Fig. 4. Limits on the mass of the scalar electron from the process $e^+e^- \to X_1X_2$ as a function of the mass of the neutral fermion X_2 and the parameter $\lambda^2 \cdot BR(X_2 \to q\bar{q}\tilde{\gamma})$ described in the text.

and the ratio of scalar quark to scalar electron mass is less than about 1.5, then decay mode (c) is expected to dominate. This is particularly true if λ^2 is small. The detection efficiency for (c) falls linearly from 0.14 for an X_2 mass of 6 GeV/c^2 to 0.06 at 22 GeV/c^2. Our experimental results yield a limit on the mass of the scalar electron as a function of the mass of X_2 and the product of λ^2 and the branching ratio for mode (c). These 90% CL limits are shown in fig. 4 and range from about 30 to 100 GeV/c^2, depending on the values of these parameters.

We note that a similar search for events with unbalanced momentum conducted by the JADE Group at the PETRA e^+e^- storage ring with an integrated luminosity of 88 pb^{-1} yielded no candidate events [9]. Limits were obtained in that search on the production of supersymmetric particles. After completing our analysis, we were informed of a similar search for monojets by the MKII Group at PEP [10].

In conclusion, we have searched for monojets in e^+e^- annihilation at 29 GeV. We find one event with a monojet originating from the interaction region. This event is consistent with the background expected from events with large-angle, initial-state radiation where the radiated photon is not detected. We set limits on the production of monojets which exclude with high probability that Z^0-mediated production of scalar particles in the mass range 2–9 GeV can account for most of the observed CERN monojet events. We cannot exclude the possibility that the CERN events arise from the Z^0-mediated production of heavy, neutral leptons. Finally, our data place some constraints on supersymmetric models.

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