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EXPERIMENTAL OBSERVATION OF EVENTS WITH LARGE MISSING TRANSVERSE ENERGY ACCOMPANIED BY A JET OR A PHOTON(S) IN $p\bar{p}$ COLLISIONS AT $\sqrt{s}$ = 540 GeV

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Abstract

We report the observation of five events in which a missing transverse energy larger than 40 GeV is associated with a narrow hadronic jet and of two similar events with a neutral electromagnetic cluster (either one or more closely spaced photons). We cannot find an explanation for such events in terms of backgrounds or within the expectations of the Standard Model.

We report here the observation of a novel type of event in which a very large missing transverse energy is associated with a single, narrow jet of hadrons or with an isolated energetic photon(s). No conventional mechanism appears to be capable of producing such events which may be due to some new physical process. The importance of an unambiguous determination of the missing energy has been amply demonstrated in the recent work which has led to the discovery of the $W^{\pm}$-particles[1].

The UA1 experiment[2] has made unique use of 4π-calorimetry. Detectors cover the full angular range down to 0.2° with a hermetic configuration and a minimal fraction of insensitive areas. Both electromagnetic and hadronic cascades are completely absorbed in the sensitive volume of the calorimeters. Furthermore, muons penetrating the detector are observed by large area wire chambers. In this way the apparently missing transverse energy can be meaningfully associated to the emission of one or more neutral, non-interacting particles. The most obvious possibility is the emission of one or several neutrinos. However in the light of recent theoretical developments, emission of photinos for instance could also give rise to energy unbalance.

For standard events where the energy balance is expected to be determined by overall calorimeter resolutions, the transverse components ΔE_y, ΔE_z of the transverse energy are neatly centred around zero and have an approximately gaussian shape with a r.m.s. width which can be well parametrized as $0.5\sqrt{|E_T|}$ where $|E_T|$ is the scalar sum (in GeV) of observed transverse energy contributions from all calorimeter cells[3]. The modulus of the resultant transverse vector $\vec{\Delta E}_M$, $|\Delta E_M| = \sqrt{\Delta E_y^2 + \Delta E_z^2}$ is distributed exponentially in the variable $|\Delta E_M^2|$ (Fig. 1).

Results are based on an integrated luminosity $\int Ldt = 0.113\ pb^{-1}$. This run was primarily oriented toward the observation of the Z^0 [4] and $W^{\pm}$ particles[5]. No dedicated trigger was provided by the requirement of the missing energy alone. An additional signature is therefore necessary in order to record the event, namely either (i) a jet of $E_T > 25$ GeV, (ii) an electromagnetic cluster of $E_T > 10$ GeV, (iii) a muon of $p_T > 5$ GeV/c, or (iv) a scalar transverse energy $|E_T| > 60$ GeV in the region $|\Delta\eta| < 1.5$.

The initial selection of events starts from a sample of 2.5×10^6

events, out of which 1.5 x 10^6 are calorimeter triggers. A first selection consists of the following requirements : (1) $|\Delta E_M| > 15$ GeV ; (2) $|E\ | < 700$ GeV to remove multiple interactions ; (3) technical cuts to remove reconstruction errors in the forward electromagnetic calorimetry (bouchons) ; (4) removal of cosmic ray and beam halo events, in which most of the energy comes from the outer calorimeter segments.

This first selection gave 29962 events which were fully reconstructed by standard UA1 programs, and ΔE_M was recalculated. A more refined selection was then performed : (1) $|\Delta E_M| > 4\sigma$ with $\sigma = 0.7 * \sqrt{|E_T|}$; (2) ΔE_M must not point to within ± 20 degrees of the vertical. This cut is necessary because of the reduced efficiency of calorimetry in that region. After this second selection 1159 events are left.

Events are then scanned by physicists on the interactive graphic facility and in most of the cases the value of ΔE_M is found to be faked by (1) cosmic rays ; (2) beam halo particles ; or (3) reconstruction problems. A total of 77 events were declared genuine. They are plotted in Fig. 2a. There are fifty identified $W^\pm \to e^\pm + \nu$ events[5] which are then removed from the sample leaving twenty-seven additional events (Fig. 2b). Their topology separates them into ;

(i) 2 events with a single, isolated neutral electromagnetic cluster

(ii) 17 events with a single-jet

(iii) 5 events with two jets

(iv) 3 events with more than two jets

We now proceed to discuss these different event topologies in turn :

<u>1. Isolated electromagnetic clusters</u>. The search for this event topology resembles very closely the selection for $W \to e\nu$ events, except that now no track must be visible in the central detector. It is therefore possible to follow an alternative road for the selection, in which the events are identified by the presence of a neutral electromagnetic cluster[5], the "photon". The inclusive spectrum of all such events with $E_T > 36$ GeV is shown in Fig. 3. One can see that there are only twelve events with $E_T >$ 44 GeV, out of which there are two which exhibit a large missing energy. Therefore we are observing a relatively large effect which associates

transversely recoiling "photons" and missing energies. The apparent ΔE_M distribution due to resolution only [3] is shown in Fig. 3 and it appears to fit the low ΔE_M events rather well. On the other hand, the probability that the two outstanding missing energy events are due to calorimeter fluctuations is exceedingly small ($< 10^{-3}$).

Several other possible background effects have been considered :

i) a $W \to e\nu$ event with the electron escaping detection in the central detector. Fig. 4 shows the polar vs azimuthal angle of all observed W events. The azimuthal angle is determined[3] by pulse division amongst the four photomultipliers in each of the layers (4) of the shower counter. The quoted accuracy (see table I) has been determined with test beam data and verified with our W sample. The narrow cross-hatched region corresponds to the insensitive volume due to the presence of a foam septum. One can see that while one of the two events (G) is inside the blind area, the other (H) is well surrounded by identified electrons from W-decay. Tracing a charged particle from the vertex to the impact point of the electromagnetic calorimeters shows that at least 20 digitizings should have been recorded in the central detector. None were observed. The possibility that an additional invisible π^0 could have hit the same e.m. detector thus shifting the centroid determination has been considered (0.002 events).

(ii) A cosmic ray track which produces an electromagnetic-like profile in the four segmentations of the shower counter. The estimated background based upon the identified tracks due to cosmic rays producing shower in the e.m. detectors is 0.001 events.

(iii) A pile-up of several neutrals, faking a photon response of the shower counter. The rate of several, neutral hits in separate counters has been used to evaluate the probability of simultaneous hits in the same shower counter (<0.007 events).

The main parameters of the two events are given in Table I. Event H is completely inconsistent with any of our background hypotheses, while for event G (Fig. 7a) the possibility of $W \to e + \nu$ cannot be excluded. Only three of our W events[5] have an electron with $E_T > 44$ GeV. No W events have been seen with $E_T > 54$ GeV, which is the case for event H.

2. Single jets. As apparent from Fig. 2b, there are several events with a single isolated jet which show spectacular missing energies (up to 70 GeV). There is a continuum of events between them and the 4σ cut near which a sharp cluster is apparent. In order to assess the background contributions to the event sample, we have relaxed the ΔE_M cut from 4σ to 2σ or 15 GeV, whichever is greater, while at the same time imposing some isolation cuts[6]. In total 117 events pass these cuts.

The main background effect is due to QCD jets, in which all but one jet are missed. To further reject this background we subtract the jet from the event and recalculate the transverse energy vector from the rest of the calorimetry. The angular distribution of this vector with respect to the jet direction[7] is shown in Fig. 5. There is a peak at $\cos\Delta\varphi = -1$, corresponding to the case where the residual transverse energy flow is opposite to the jet, as expected from QCD background and clearly visible in our jet data sample[8]. For comparison the corresponding distribution for $W \rightarrow e\nu$ does not exhibit such a strong spike around $\cos\Delta\varphi = -1$. Therefore events with $\cos\Delta\varphi < -0.8$ have then been rejected. The six events with largest ΔE_M^2 of Fig. 2b pass the cut. The distribution $dN/d\Delta E_M^2$ is given in Fig. 6. In order to evaluate the background we have then taken a sample of jet events and "fluctuated" the calorimeter response to the jets[3] as well as to the non-jet part of the event in order to simulate single-jet events from variations in the response of the detector. The result of this calculation shows (Fig. 6) that both the absolute number and the ΔE_M distributions of the events with $\Delta E_M < 30$ GeV are consistent with this background, which vanishes exponentially for $\Delta E_M > 30$ GeV. Clearly events labelled A → F cannot be due to this effect.

Another contribution can come from $W \rightarrow \tau + \nu_\tau$ in which the τ-decay is called the "jet". A full detector simulation gives the result shown in Fig. 6. Nine events are expected, mostly in the region dominated by QCD background. Event F is in the region where we would expect about one event, while the others (A → E) are beyond the kinematic limit for the decay process. Likewise, the contribution from a hypothetical new sequential lepton of mass > 20 GeV/c^2 is at the level of a few events with a spectrum slightly softer than from $W \rightarrow \tau\nu$.

Finally the possibility of a QCD jet produced in association with an "invisible" $Z^0 \rightarrow \nu\bar{\nu}$ decay has been considered. Events of the type W + jet and Z^0 + jet have been observed[5] and they appear in excellent agreement with QCD predictions. There is no appreciable contribution predicted for our values of E_T.

The contributions due to charm and beauty decays have been calculated with the help of ISAJET[9], leading to less than 0.1 isolated single-jet events with $\Delta E_M > 40$ GeV. We remark that any background of this type (including hypothetical heavy new flavours), should also give events with e or μ instead of missing energy recoiling against a jet. A direct search for such events (both e and μ with $E_T > 40$ GeV) has given a negative result.

We are therefore left with five outstanding events. Parameters of the six highest ΔE_M events are given in Table II. We shall describe them briefly :

(i) Event A (Fig. 7b). The most striking characteristic of this event is the presence of a very high momentum (80^{+20}_{-13} GeV/c) track measured in the central detector, which penetrates more than 12 interaction lengths of the calorimetry. This track is observed as a single clean track in the muon chambers. We have an independent measurement of the muon momentum mainly due to the deflection in the magnetized iron from the reconstructed track in the muon chamber[5]. The charge and magnitude of momentum (105^{+59}_{-27}) GeV/c is consistent with the central detector measurement. The probability for this track to be a pion or kaon decay about 3×10^{-3}, and it is therefore likely to be a prompt muon. Also it would be a rather unusual fragmentation for an ordinary jet. The rest of the jet is made up of a 12.4 GeV transverse energy electromagnetic shower and a 13 GeV neutral hadronic shower, at a finite angle ($\sim$ 0.1 radian) with respect to the muon since they hit separate segments. The invariant mass of the muon-calorimeter cluster is about 5 GeV. There are no other charged tracks hitting the calorimeter cluster. The overall activity of the event is modest ; only 21 charged tracks are observed in the entire interaction.

(ii) Event B (Fig. 7c). The jet structure in this event consists of a narrow cone of two positive and one negative hard tracks (23 GeV/c total transverse momentum) and a low invariant mass ($\sim$ 0.8 GeV/c^2).

(iii) Event C. This event has the most activity outside the main jet. The scalar $|E_T|$ = 129 GeV, but there is no strong jet structure besides the main jet. Not all charged tracks in the main jet are measurable due to the very small angle the jet makes with respect to the magnetic field direction.

(iv) Event D. The shower from the jet in this event is almost purely electromagnetic. The jet contains four charged particles. Two of these tracks are clearly not associated to the primary vertex and fit a K^0 mass (0.470 ± 0.020) GeV/c^2. The highest momentum track has 13 GeV/c. The probability of a pion of this momentum to be completely absorbed in the shower counters is reasonably high (about 10%) and there is no clear π/e separation at this energy. The invariant mass of the four charged particles is about 3.1 GeV/c^2.

(iv) Events E and F are also described in Table II. Event E has other visible tracks which cannot be measured due to their small angle with respect to the magnetic field besides the two listed in Table II. Event F might be due to $W \rightarrow \tau + \nu_\tau$ decay, in which one of the three decay tracks is soft.

3. <u>Multijets</u>. Our sample contains 8 such events, all but one very near to the 4σ cut. A preliminary background estimate indicates that they are most likely compatible with background from QCD and heavy flavour decays. Therefore at the present stage they are not further considered.

4. <u>Conclusions</u>. We have presented a sample of five single-jet events and two "photon" events with ΔE_M > 40 GeV. We have been unable to find a reasonable explanation in terms of background including W and Z^0 decays or within the expectation of the Standard Model. Therefore we believe they are due to some new physical phenomenon. The spectacular values of the transverse energies are apparent on Fig. 8 and the transverse masses given in Table II appear to exceed the corresponding values for W and Z^0 decays.

At the present time we can only speculate about the origin of this new effect. The missing transverse energy can be due either to:

(i) one or more prompt neutrinos

(ii) any invisible Z^0, such as $Z^0 \to \nu\bar{\nu}$ decay, which is expected to have a large (18%) branching ratio. Note that the corresponding decays into charged lepton pairs $Z^0 \to e^+e^-$, $Z^0 \to \mu^+\mu^-$ have lower branching ratios ($\sim$ 3%) and may not have yet been produced within the present statistics.

(iii) new, non-interacting neutral particles.

The jets appear somewhat narrower and with lower multiplicities than the corresponding QCD jets, although it might be premature to draw conclusions on such limited statistics.

A number of theoretical speculations[10)] maybe relevant to these results. We mention briefly the possibilities[11)] of excited quarks or leptons and of composite, coloured or supersymmetric W's and Higgs. A recent calculation[11)] has been made in the context of the present collider experiment, on the rate of events with large missing transverse energy from gluino pair production with each gluino decaying into a quark, antiquark, and photino. The non-interacting photinos may produce large apparent missing energy. For instance, the calculation gives an expectation of about 100 single-jet events with $\Delta E_M > 20$ GeV for a gluino mass of 20 GeV/c^2. Taking our excess of 5 events above background as an upper limit for such a process, we deduce that the gluino mass must be greater than about 40 GeV/c^2.

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The UA1 Collaboration is preparing a comprehensive report on the detector (ed. H. Wahl) 1984, to be published in Nucl. Instrum. Methods (NIM).

Ref. 3. A very elaborate study of the performance of the detector has been performed using test beam data, real events, and Monte Carlo simulation. The geometry included in the Monte Carlo includes all shower fluctuation effects, cracks in the apparatus, punch through effects of hadrons, and reconstruction procedures. A particularly useful calculation was performed with a single jet generator using the experimentally observed fragmentation functions and with which one has mapped the jet resolution over the whole detector solid angle.

Ref. 4. G. Arnison et al., Phys. Lett. 126B (1983) 398.

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Ref. 6. Events are rejected if either :
i) a jet, found in the calorimeter or in the central detector, is emitted within ± 20 degrees in azimuth from the vertical plane. This cut removes events where particles escape between joining elements of the calorimeters.
ii) The missing transverse energy vector lies within less than 100 degrees in azimuth from a calorimeter or central detector jet. This cut removes large fluctuations on the measured energy of one of the jets.

Ref. 7. We remark that there is a bias which shifts the cos$\Delta\varphi$ distribution to the negative side due to over-subtraction of the jet. The contribution of random particles from the rapidity plateau which fluctuate into the $\Delta R=1$ cone (in η,φ space) which defines the jet is on the average about 2 GeV.

Ref. 8. G. Arnison et al., Phys. Lett. 132B (1983) 214 ; ibid 132B (1983) 223. The transverse energy threshold for definition of a jet has been set to 12 GeV.

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Figure Captions

Fig. 1. Distribution of missing energy squared normalized to the total scalar transverse energy observed for a sample of jet triggers. The solid curve is a Monte Carlo simulation.

Fig. 2a. Scatter plot of missing energy squared vs total scalar transverse energy for events which have missing energy in excess of 4 standard deviations. Cosmic rays, beam halo and events with reconstruction problems are removed. Events identified as $W \to e\nu$ decays are labeled with a cross and other events are labelled with a solid circle.

2b. Same as a with the $W \to e\nu$ events removed. The event topology is indicated as single jet (solid circle), photon(s) (cross), 2-jet events (open circle) and 3 or more jet events (triangle).

Fig. 3. Scatter plot of E_T of photon(s) vs ΔE_m^2 for all events with an isolated neutral electromagnetic cluster.

Fig. 4. Electron polar angle (with respect to the beam axis) vs azimuthal angle for all $W \to e\nu$ decays (solid circles) and the two photon candidates (open circles). The dashed contour indicates the region beyond which at least 20 digitizings are expected in the central tracking chambers.

Fig. 5. Angle between the residual transverse energy direction (jet subtracted) and the jet direction for event candidates with one jet ($E_T^{jet} > 12$ GeV).

Fig. 6. Distribution of missing transverse energy squared for events with $\cos\Delta\varphi > -0.8$ (see text). The solid curve is the background expected from jet fluctuations. The dashed curve is the expected contribution from $W \to \tau\nu$.

Fig. 7. Display of calorimeter cells and tracks with transverse energy greater than 1 GeV along with transverse energy flow (φ vs η)

seen in calorimeters and in charged tracks for a) event H b) event A and c) event B.

Fig. 8. Scatter plot of missing E_T vs jet or photon(s) E_T from events A-H.

Table I
Properties of the isolated "photon" events

Run, event	General event properties					Shower counter measurement							
	E_{tot} (GeV)	$\|E_T\|$ (GeV)	ΔE_M (GeV)	E_T (γ) (GeV)	m_T (γ, ΔE_M) (GeV/c^2)	E_{tot} (GeV)	Electromagnetic samples (GeV)				Had. energy (GeV)	η†)	$\phi \pm \Delta\phi$*) (deg)
							S_1	S_2	S_3	S_4			
H 8167 90	298	91	40 ± 4	54	93 ± 5	54.4	4.1	35.0	15.1	0.2	0.0	0.14	16 ± 2
G 7856 1020	390	104	40 ± 6	44	84 ± 6	53.3	3.1	31.4	18.1	0.7	0.0	0.65	1 ± 2

†) Rapidity is defined as positive in the antiproton direction.

*) The azimuthal angle $\phi = 0$ corresponds to the horizontal direction.

Table II
Properties of single jet events

Run, event	General event properties				Jet properties					
	E_{tot} (GeV)	$\|E_T\|$ (GeV)	ΔE_M (GeV)	$m_T(\text{JET}, \Delta E_M)$ (GeV/c²)	E_T (GeV)	E_T^{elm} a) (GeV)	ϕ b) (deg)	η c)	$p_T \pm \Delta p_T$ d) (GeV/c)	m_{CH} (GeV/c²)
A 7325 808	300	48 94*	24 ± 4.8 (66 ± 8)*	130 ± 16	25 71*	12.4	152	-1.13	$+46^{+12}_{-8}$	SINGLE TRACK
B 7157 506	294	90	59 ± 7	106 ± 12	48	23.3	-142	-0.39	$-7.3^{+1.2}_{-0.9}$ $+10.1^{+2.5}_{-1.7}$ $+3.7^{+0.2}_{+0.18}$	0.79 ± 0.12
C 7513 1212	489	129	46 ± 8	97 ± 17	52	44.4	176	-0.03	$-2.9^{+0.35}_{-0.29}$	e)
D 7304 1270	279	75	42 ± 6	85 ± 12	43	42.1	-34	-0.04	$-13.0^{+5.5}_{-3.0}$ K^0 { $-1.83^{+0.07}_{-0.065}$, $+0.92^{+0.012}_{-0.12}$ } $+0.89^{+0.07}_{-0.007}$	3.14 ± 0.38
E 8072 615	398	92	41 ± 7	87 ± 14	46	29.9	173	0.62	$+0.86^{+0.051}_{-0.045}$ $-0.61^{+0.04}_{-0.04}$	UNRECONSTRUCTED TRACKS
F 8032 1158	405	93	34 ± 7	73 ± 14	39	36.2	41	-0.31	$-4.8^{+0.32}_{-0.28}$ $-7.6^{+0.8}_{-0.66}$	0.517 ± 0.06

a) Electromagnetic part of the jet transverse energy.

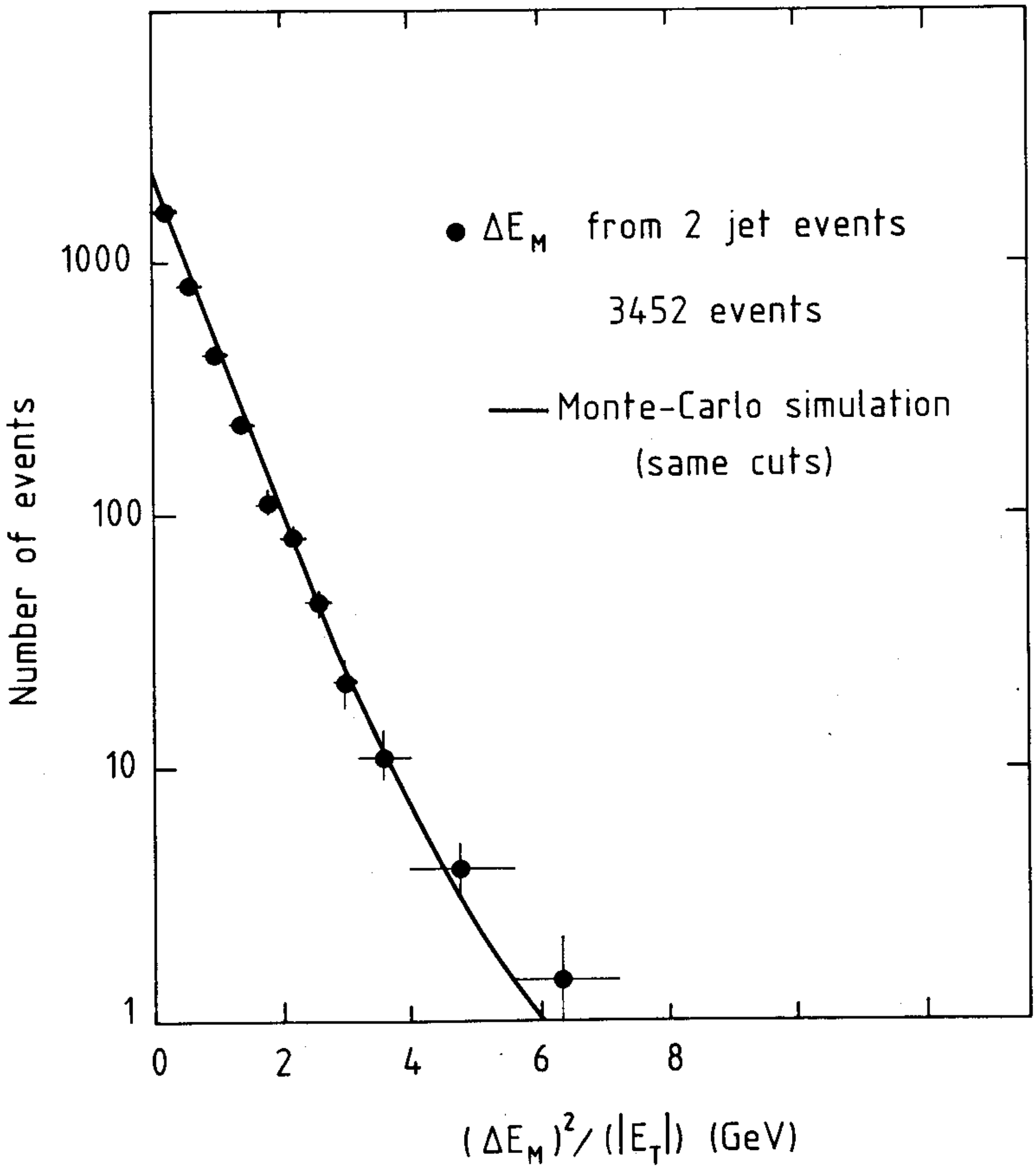
b) Azimuthal angle ϕ.

c) The rapidity η is defined as positive in the direction of outgoing $\bar{p}$.

d) Charged tracks associated to the jet with $p_T > 0.5$ GeV/c. The errors are statistical only.

e) This event could have other unreconstructed tracks in the horizontal plane.

*) Including the muon momentum in the calculation.



● ΔE_M from 2 jet events
3452 events
—— Monte-Carlo simulation
(same cuts)
Number of events
1000
100
10
1
0
2
4
6
8
$(\Delta E_M)^2/(|E_T|)$ (GeV)

Figure 1

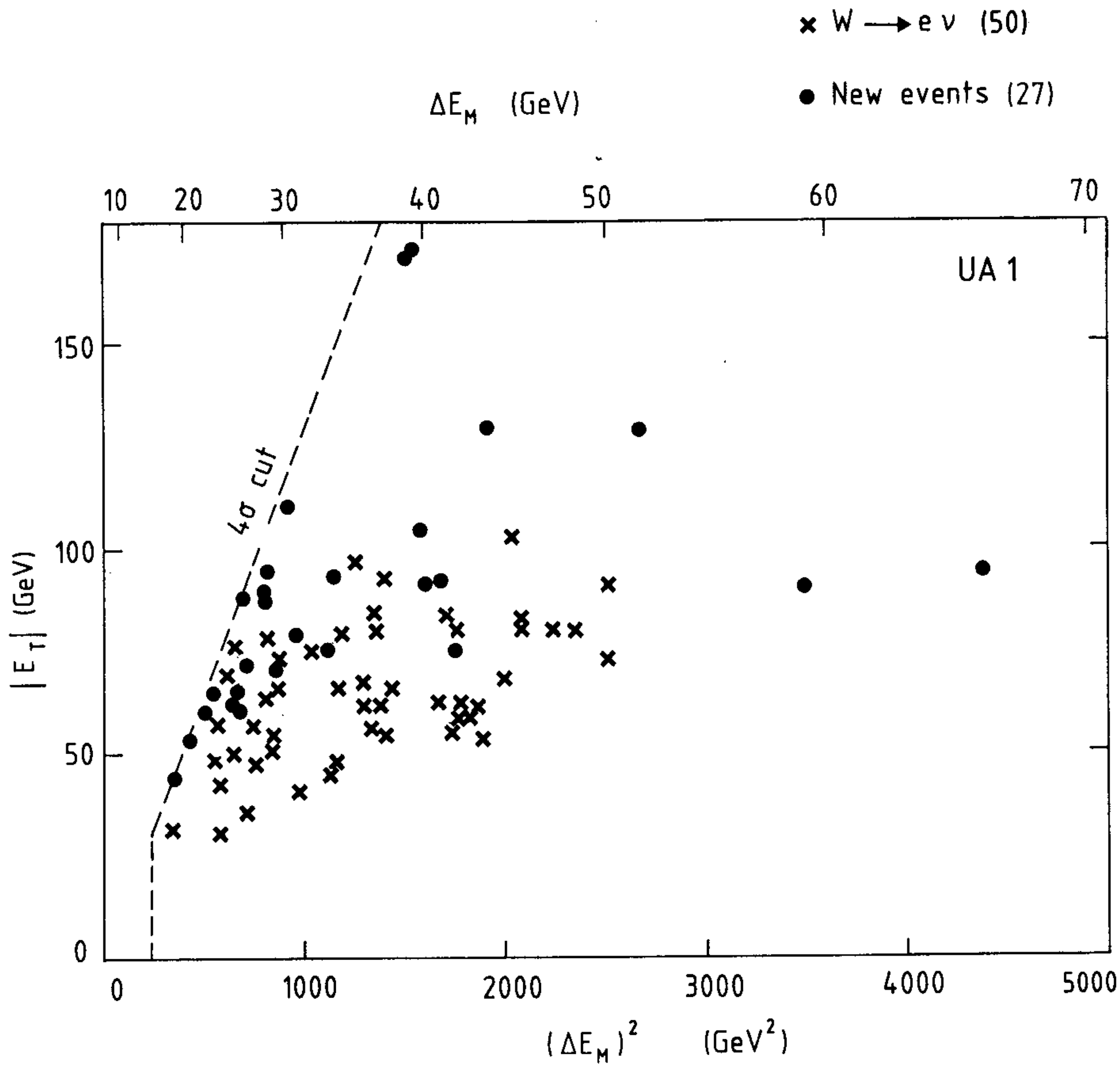

× W → e ν (50)
● New events (27)
ΔE_M (GeV)
10 20 30 40 50 60 70
UA 1
4σ cut
|E_T| (GeV)
0 50 100 150
0 1000 2000 3000 4000 5000
(ΔE_M)^2 (GeV^2)

Figure 2a

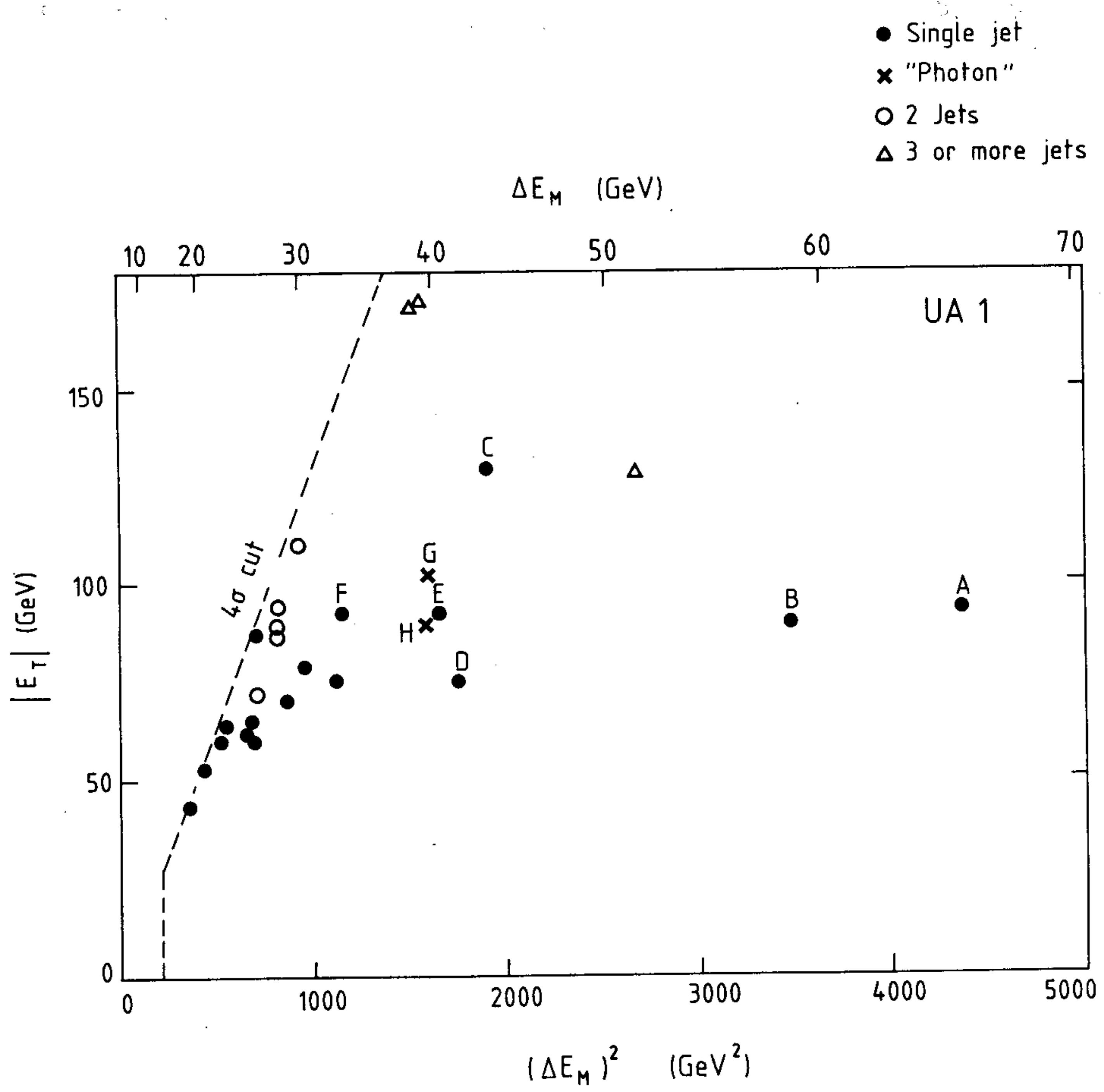
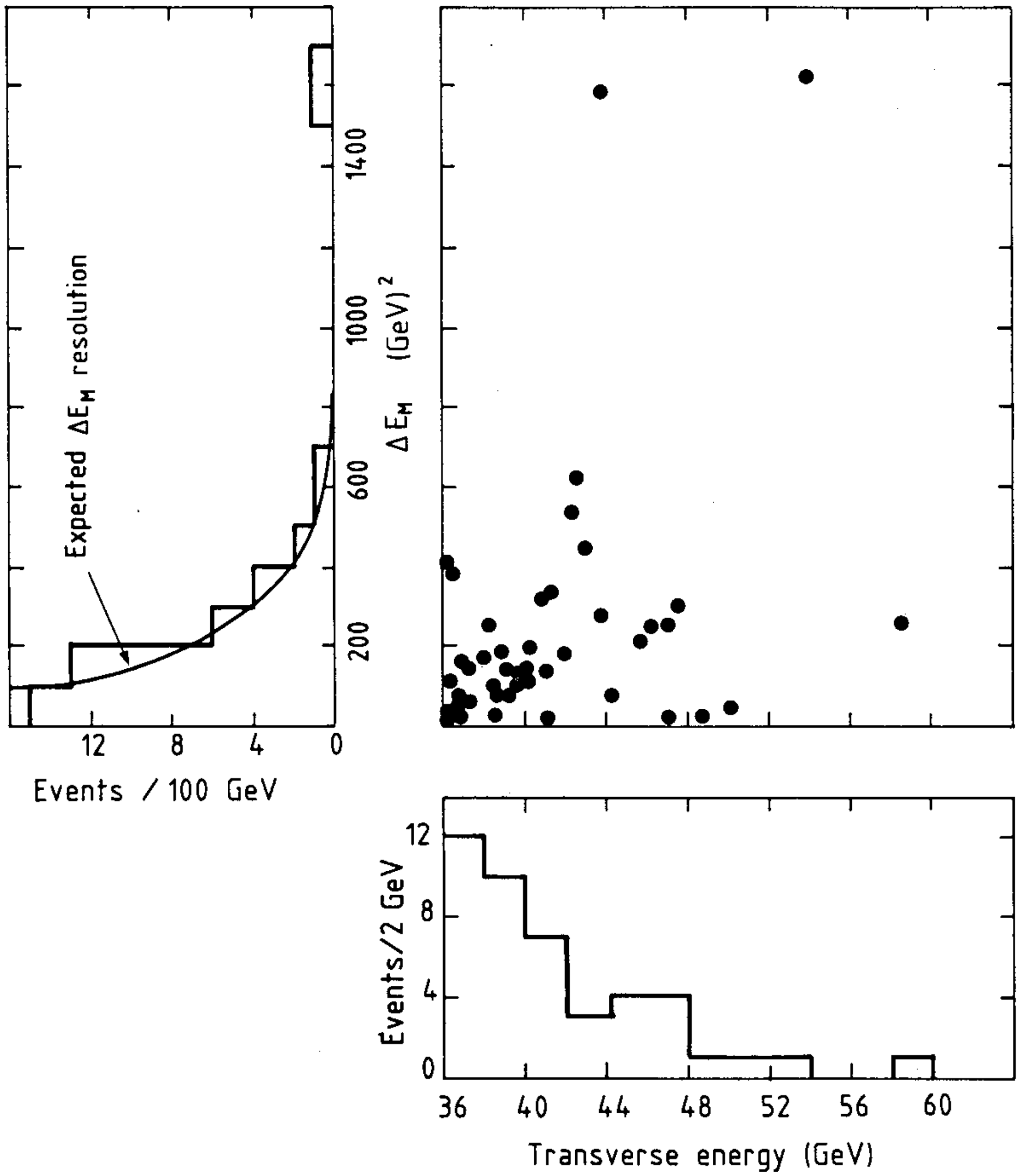

● Single jet
× "Photon"
○ 2 Jets
△ 3 or more jets
ΔE_M (GeV)
10
20
30
40
50
60
70
UA 1
150
100
50
0
|E_T| (GeV)
4σ cut
A
B
C
D
E
F
G
H
0
1000
2000
3000
4000
5000
(ΔE_M)^2 (GeV^2)

Figure 2b



Expected ΔE_M resolution
Events / 100 GeV
ΔE_M (GeV)^2
200
600
1000
1400
12
8
4
0
Events/2 GeV
Transverse energy (GeV)
36
40
44
48
52
56
60

Figure 3

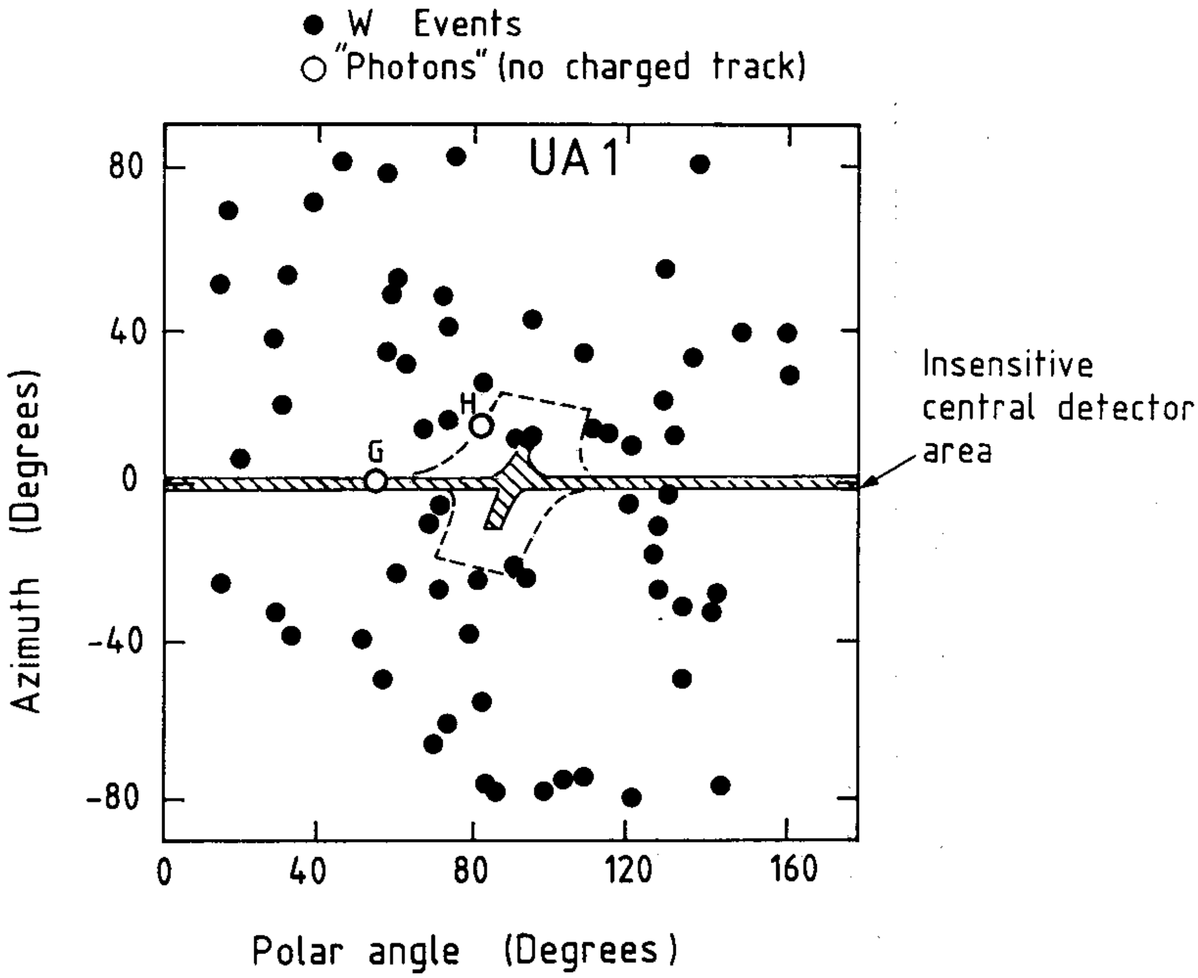

W Events
"Photons" (no charged track)
UA1
80
40
0
-40
-80
Azimuth (Degrees)
H
G
Insensitive central detector area
0
40
80
120
160
Polar angle (Degrees)

Figure 4

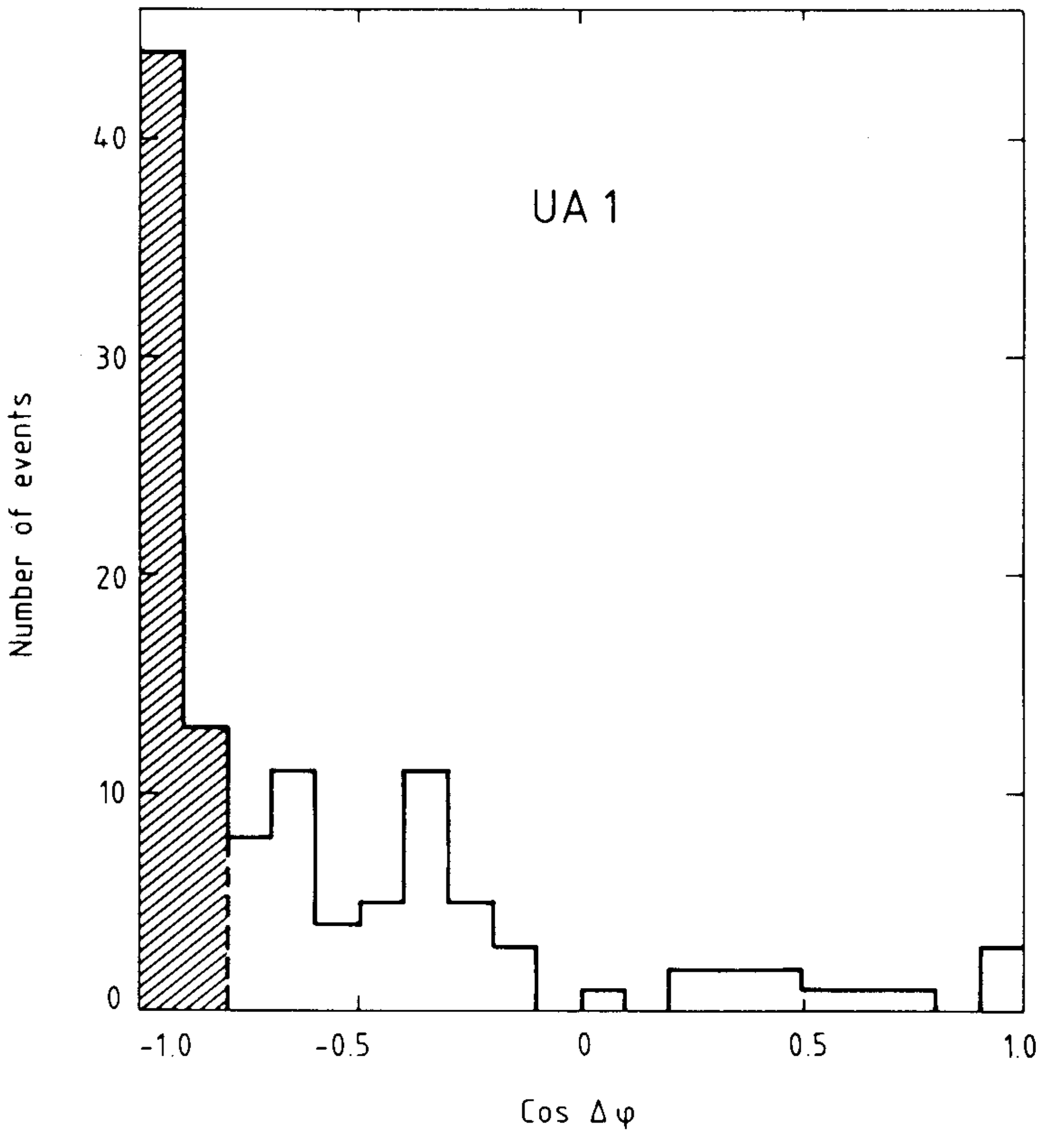
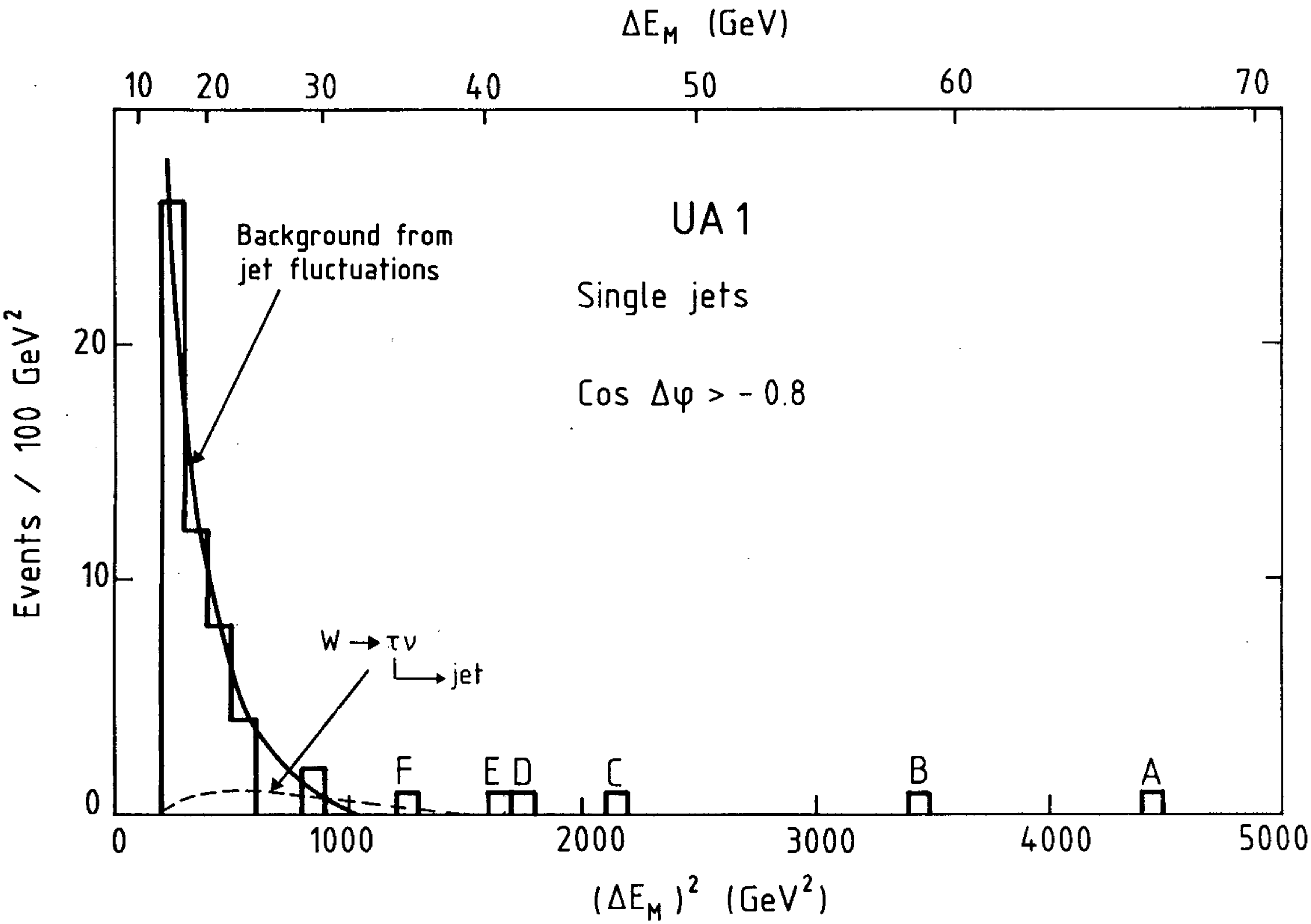


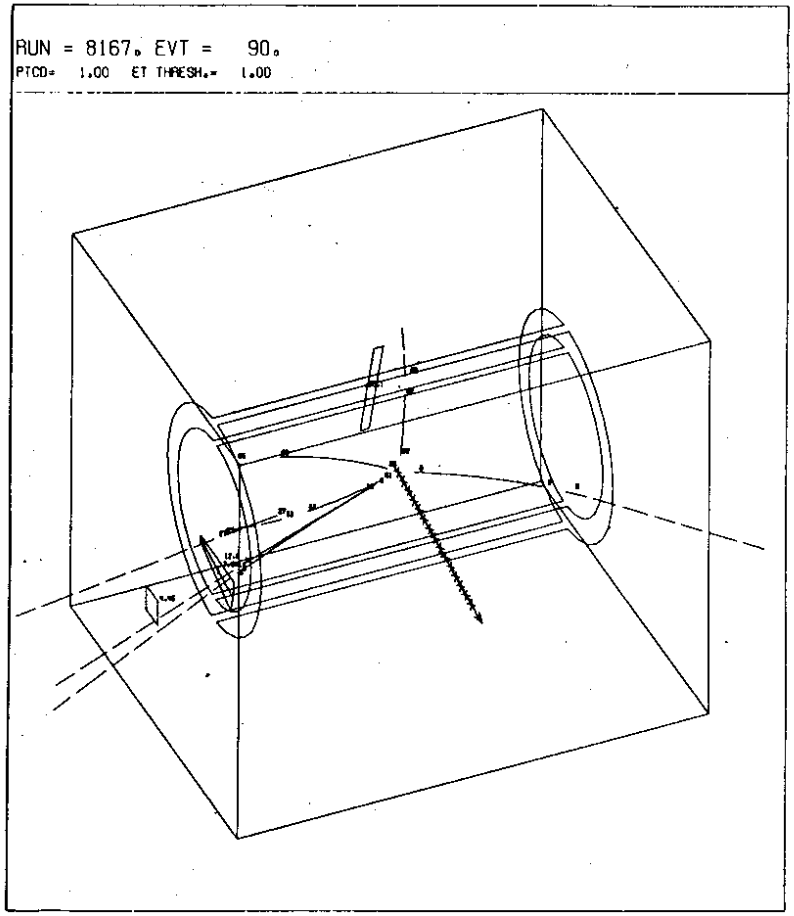
Figure 5



ΔE_M (GeV)
10
20
30
40
50
60
70
UA 1
Single jets
Cos Δφ > - 0.8
Background from
jet fluctuations
W → τν
→ jet
F
E D
C
B
A
Events / 100 GeV²
20
10
0
0
1000
2000
3000
4000
5000
(ΔE_M)² (GeV²)

Figure 6

Event H



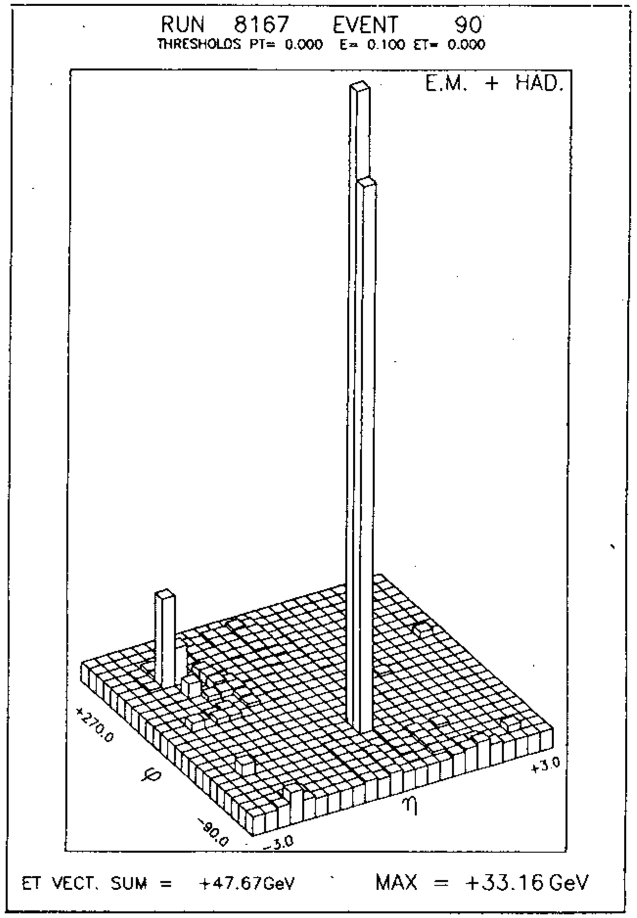
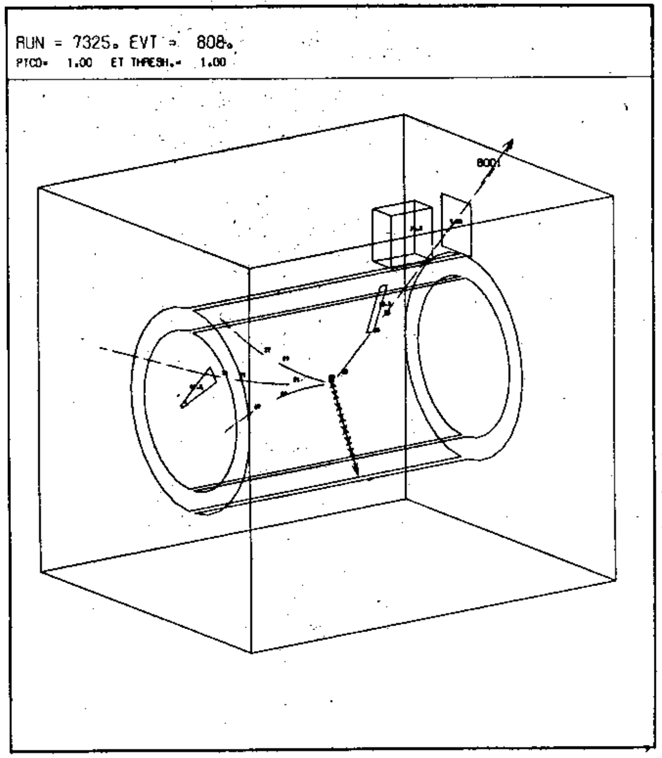
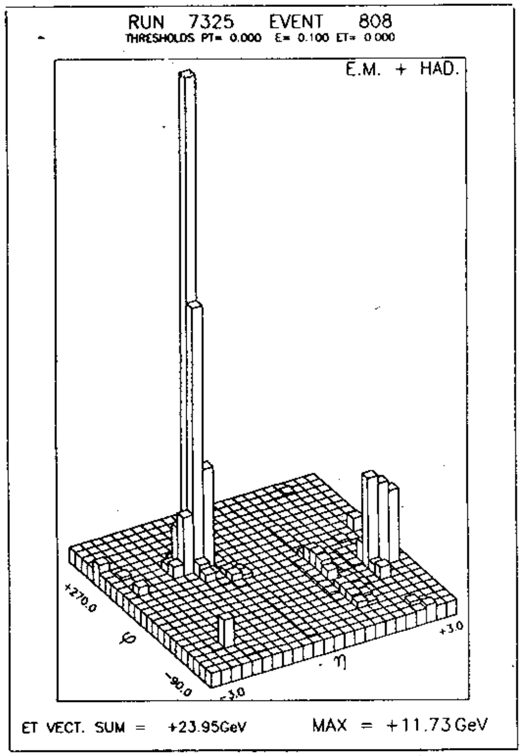


Figure 7a

Event A





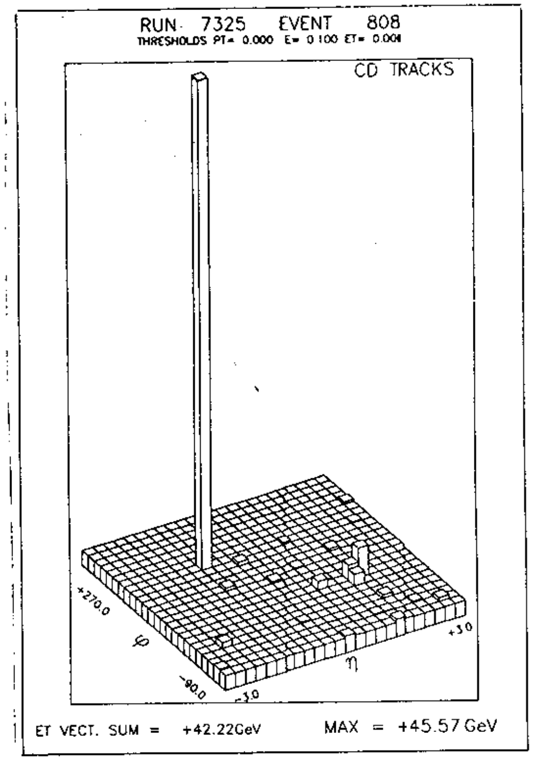


Figure 7b

Event B

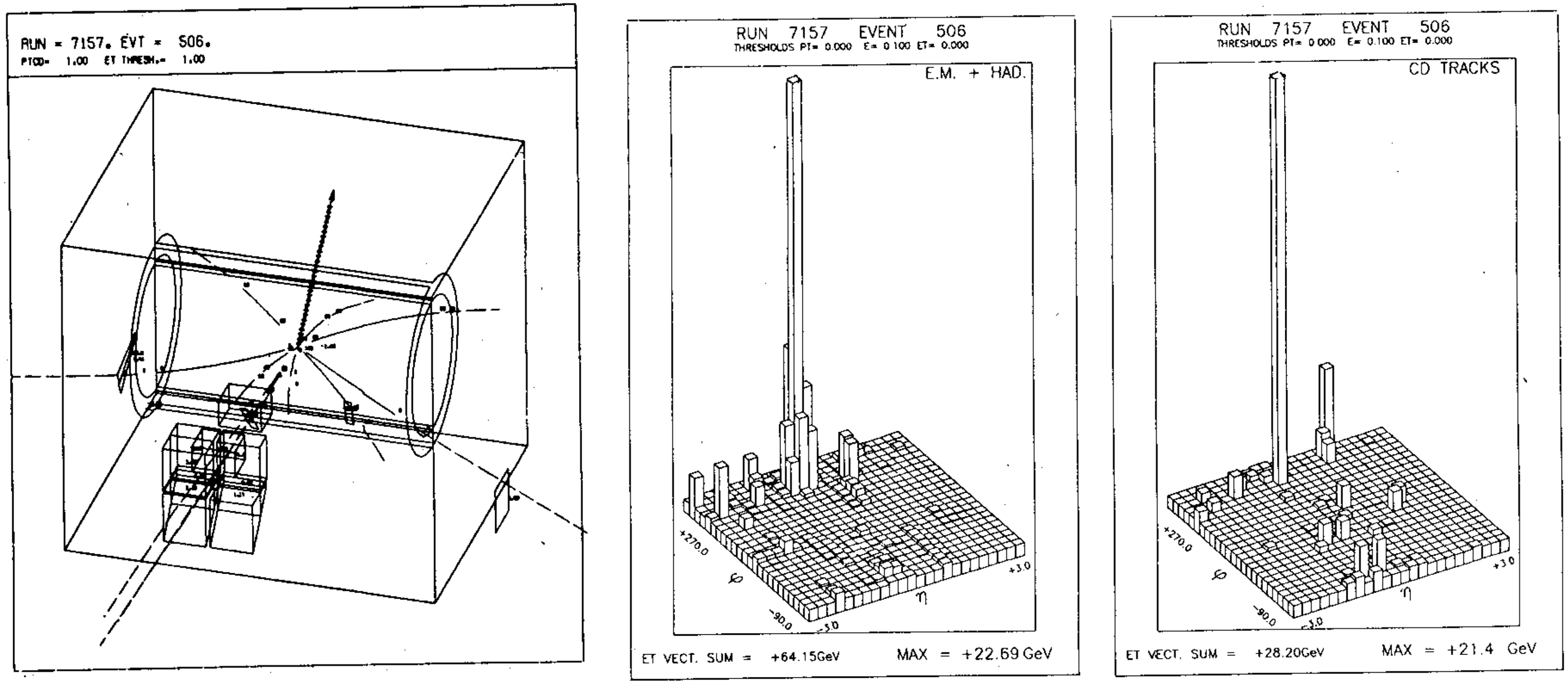
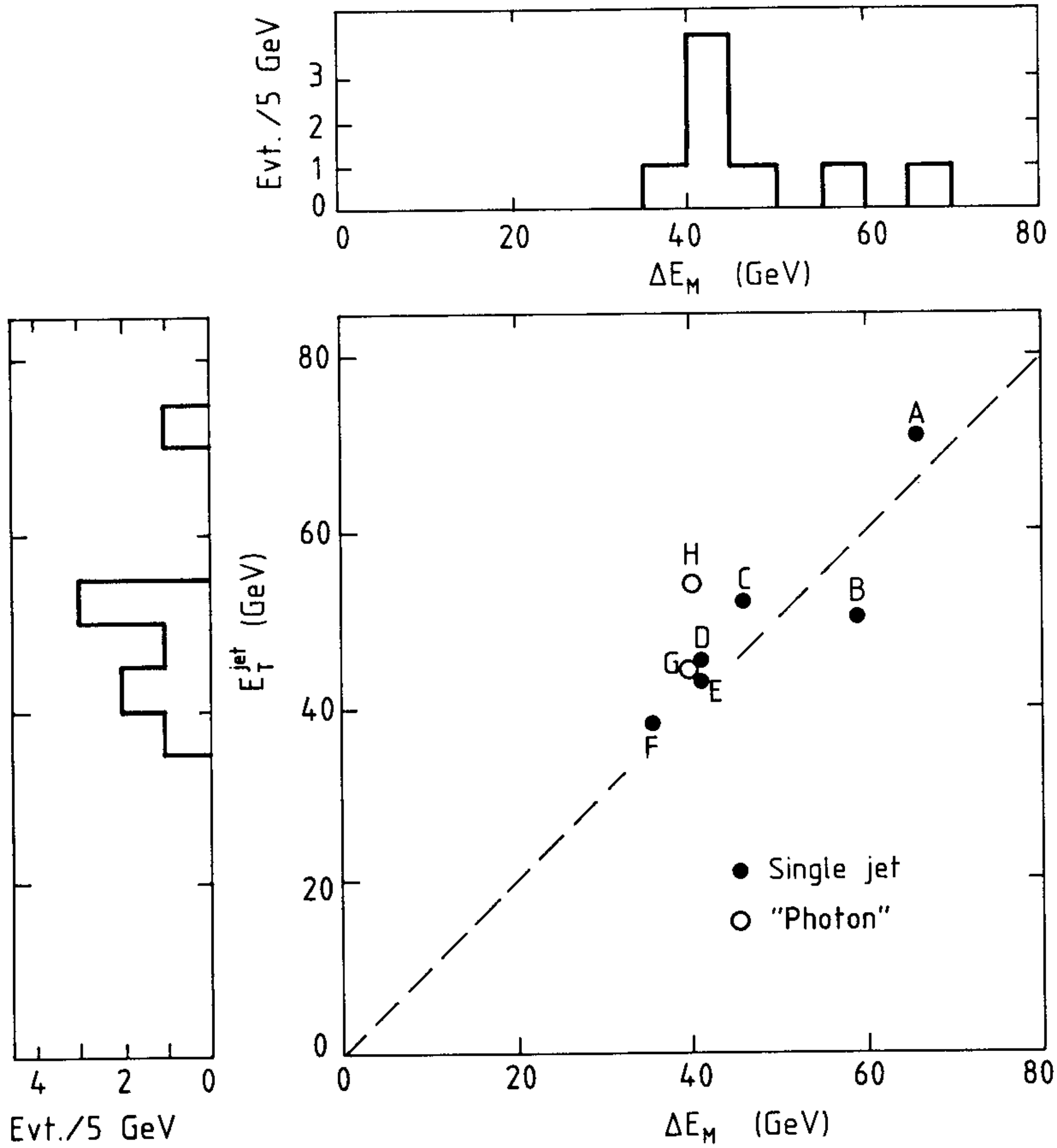


Figure 7c



Evt. /5 GeV
3
2
1
0
0
20
40
60
80
ΔE_M (GeV)
80
60
40
20
0
4
2
0
Evt./5 GeV
E_T^{jet} (GeV)
A
B
C
D
E
F
G
H
Single jet
"Photon"
0
20
40
60
80
ΔE_M (GeV)

Figure 8