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An accelerator search at 900 GeV c.m. energy for the Centauro phenomenon

UA5 Collaboration
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ABSTRACT

A search for the Centauro phenomenon has been made at $\sqrt{s} = 900$ GeV using the UA5 detector at the SPS $\bar{p}p$ collider operated in a pulsed mode. Possible interpretations of the cosmic ray data are discussed leading to various analyses of our data which exploit the distinctive features of the Centauro events: high multiplicity, high p_T and absence of produced photons. No indication of Centauro production is observed. Upper limits on the production of Centauros at the level of a few per thousand inelastic events are obtained.

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1. Introduction

Cosmic ray studies of high energy hadronic interactions in the laboratory energy region from 100 to 10000 TeV have mainly been carried out using large emulsion chambers [1]. With the start of the CERN SPS $\bar{p}p$ Collider in 1981 the cosmic ray data have been compared directly with the detailed accelerator-based data at a c.m. energy of 546 GeV, corresponding to a laboratory energy of 159 TeV, and the agreement has been found to be good [2]. Higher energy cosmic ray data, however, indicate the existence of several anomalous phenomena [1]. Among these, the phenomenon which has received the widest attention is referred to as CENTAURO [1,3]. The Centauro events are characterized by high multiplicity and high transverse momenta with an almost complete absence of photons (and hence of π^0) among the produced particles.

Such an event could be the result of a collision between a projectile nucleon(*) of an estimated energy of about 1500 TeV [1] (equivalent to a c.m. energy $\sqrt{s} \sim 1700$ GeV) and an atmospheric nucleon. In 1981 the SPS Collider offered the highest available c.m. energy at an accelerator and so searches for the Centauro phenomenon were made among the high multiplicity data [4,5]. However, no candidates were found. A possible explanation of this negative result could be the existence of a threshold for Centauro production between 546 GeV and 1700 GeV c.m. energy.

In 1982 a scheme was suggested to increase the c.m. energy to 900 GeV by operating the CERN collider in a pulsed mode [6] and the proposed operation was successfully achieved in March 1985. In this paper we report on our search for the Centauro phenomenon at this higher energy of $\sqrt{s} = 900$ GeV, corresponding to a laboratory energy of 431 TeV.

(*) Even though the primary cosmic rays contain iron nuclei, the interactions observed in the emulsion chambers must all be induced by nucleons. Since the chamber is situated at a depth of 540 g/cm^2, (17 interaction lengths for iron), the nuclei would have broken up.

2. The UA5 Detector

The UA5 detector and standard analysis procedures have been described in detail elsewhere [7]. Two large streamer chambers, having a visible region of 6m x 1.25m x 0.5m, were placed above and below the beam pipe. The geometrical acceptance was about 95% for $|\eta|<3$, falling to zero at $|\eta| = 5$ (η is the pseudorapidity, $\eta = -\ell n \tan \theta/2$, where θ is the c.m. emission angle). The triggers were provided by hodoscopes of scintillation counters called A1 and A2 at each end of the detector covering the pseudorapidity range $2 < |\eta| < 5.6$. The triggers used were a 2-arm trigger (A1.A2, i.e. at least one hit at each end) and a 1-arm trigger ($A1.\overline{A2}$, i.e. hits at only one end). More details concerning the trigger may be found elsewhere [8].

Since our earlier search for the Centauro phenomenon [4], the UA5 detector has been significantly improved in several ways: by adding a small calorimeter, by replacing the stainless steel beam pipe by a 2mm thick beryllium beam pipe and by introducing, for part of the run, a lead converter plate between the beam pipe and the upper chamber to improve the photon conversion efficiency. The lead-iron-scintillator calorimeter was situated at 90° beside the lower streamer chamber and covered the interval $|\eta| \lesssim 0.9$ and $\Delta\phi \simeq 30°$, where ϕ is the azimuthal angle around the beam axis. One absorption length of lead was followed by three absorption lengths of iron and each part was instrumented with scintillator readouts [7,9]. The photon converter [10] consisted of an aluminium box containing four 0.5 mm thick lead sheets, of varying sizes so as to give a roughly uniform photon conversion probability (~ 25%) for the upper streamer chamber over the rapidity range $|\eta|<3$. Photon detection in the region $3<|\eta|<4.5$ was provided by conversions in the beryllium pipe and more particularly in the aluminium flanges connecting different beryllium segments.

During the run of 1985 the UA5 experiment recorded about 500 000 triggers of which about 115 000 were on film. Data were taken with 1-arm and 2-arm triggers at 200 GeV, 900 GeV and at intermediate energies. The sample of fully measured and reconstructed events at 900 GeV available for the present analysis consisted of 5154 2-arm triggers, of which 860 included the photon converter, 491 1-arm triggers and a special sample of 480 events having a substantial energy in the calorimeter, 88 of which included the photon converter.

3. Expectations for Centauro events at $\sqrt{s}$ = 900 GeV

In order to see how Centauro events should appear in our detector we start by summarizing some important features of the Mt. Chacaltaya emulsion chamber data [1]. From this we estimate the likely properties of such events at $\sqrt{s}$ = 900 GeV, and describe corresponding Monte Carlo simulations with which the data have been compared.

The threshold in energy for detecting a shower in the Chacaltaya detector is about 1 TeV [1]. This energy refers to the electromagnetic cascade initiated by the γ, $e^{\pm}$ or hadron. In the case of a hadron the observed energy is the fraction k_γ of its energy which goes into π^os; for mesons $k_\gamma \sim 1/3$ while for nucleons $k_\gamma \sim 1/5$. Thus if the hadrons produced in an interaction have $\langle p_T \rangle \sim 0.5$ GeV/c the energy threshold means that the Chacaltaya detector is only sensitive to particles emitted at extreme forward angles, corresponding to pseudorapidities $\eta \gtrsim 9$. For comparison, at the typical c.m. energy of the observed Centauro events, $\sqrt{s}$ = 1700 GeV, the projectile has rapidity 15, and the centre-of-mass has rapidity 7.5 in the laboratory, and thus only part of the forward hemisphere is seen.

In the first Centauro event, Centauro I, the average transverse momentum of observed showers was estimated [1,3] to be 0.35 ± 0.14 GeV/c. Thus taking $k_\gamma \sim 1/3$ to 1/5 we may estimate the $\langle p_T \rangle$ of the produced hadrons to be in the range 1 to 2 GeV/c. In the Centauro events the pseudorapidities of the observed showers are spread over 4 units from $\eta_{lab} \sim 8.5$ to 12.5. For example, fig.1 shows the pseudorapidity distribution of Centauro I [3]. From the observed number of showers the corrected multiplicity and interaction energy may be obtained by applying the following corrections:

a) some hadrons will pass through the chamber without interacting, as the emulsion chamber is only about 1.5 interaction lengths deep;

b) some hadrons will interact in the atmosphere before reaching the emulsion chamber;

c) some hadrons will be below the detection threshold.

The corrections a) and b) are relatively straightforward to make. However, correction c) is more dependent on the assumed production process of the Centauro event. Two possibilities which are compatible with the data are:

i) the isotropic decay of a massive object ("fireball") of mass $\sim 250\ \text{GeV}/c^2$. Such an interpretation is favoured by the Brasil-Japan group [1], and in this case the correction for hadrons below threshold is quite small (~20%). The Chacaltaya group derive this correction by extrapolating the integral energy distribution of the observed showers to zero using an exponential fit. On this basis the event multiplicity is estimated to be ~ 100 hadrons. This interpretation is shown as the dashed curve in fig. 1.

ii) p_T limited (cylindrical) phase space (CPS) could also be consistent with the data, since the rapidity range of the observed particles is not large enough to distinguish this from the fireball hypothesis. In this case we use the corrected hadron density $dN/d\eta \sim 25$ in the acceptance region of the emulsion chamber and assume the η distribution is symmetric about zero in the centre-of-mass system, to obtain an estimate of ~ 200 hadrons produced. The solid curve in fig.1 shows this interpretation in comparison with the data.

To account for the almost complete absence of photons (and therefore of π^o's) amongst the produced particles the Brasil-Japan group [1] has favoured the assumption that the produced hadrons consist entirely of baryons and antibaryons. Although there is no direct evidence for this extreme assumption it appears to us to be the simplest way to account for the lack of photons in Centauro events.

In the light of these considerations we have written two event generators for "Centauro" events. Both are in fact simple modifications of our existing Monte Carlo programs [11].

i) Diffractive type: We generate a system of mass 250±25 GeV/c^2 recoiling against a proton or antiproton. The "fireball" then decays isotropically to typically 100 hadrons comprised of equal numbers of $p, \bar{p}$, n and $\bar{n}$ on average. With these assumptions $\langle p_T \rangle$ = 1.7 GeV/c is obtained in good agreement with the Chacaltaya data for $k_\gamma = 0.2$.

ii) CPS type: We modify the standard UA5 cluster model [11] to produce no π^0's (or photons) and require the final state to be dominantly nucleons and antinucleons. In this case it is necessary to scale the multiplicity of the observed Centauros at $\sqrt{s}$ = 1700 GeV to $\sqrt{s}$ = 900 GeV. The c.m. rapidity of both beam and the target move in by 0.5 units, so we guess the width of the Centauro rapidity distribution shrinks from 4 to 3.5 units. Furthermore, the average central particle density in rapidity $\rho(0)$ for normal events grows with $\sqrt{s}$ [12], from which we estimate $\rho(0)$ to be 10% higher at $\sqrt{s}$ = 1700 GeV than at 900 GeV. We thus expect a hadron multiplicity of ~ 200 x 3.5/4 x 0.9 = 150, and accordingly set $\langle n_{ch} \rangle = 75$, with a Poisson distribution. We have generated "Centauro" events of this type using values of $\langle p_T \rangle$, within the range 0.8 to 2.0 GeV/c, covering the range expected from cosmic ray data. In the discussion below, a sample of Monte Carlo events with $\langle p_T \rangle$ = 1.45 GeV/c will be used for illustration.

In sections 4 and 5 we shall describe various searches for the CPS-type Centauros. The diffractive type Centauros will have different triggering characteristics in our detector, and a separate search for such events will be presented in section 6. The characteristics of Centauro events that we will use in our searches are high multiplicity, high transverse momentum and absence of converted photons in the streamer chamber or of electromagnetic energy in the calorimeter.

4. Analysis of the calorimeter data

In fig. 2a, we show the spectrum of total transverse energy in the calorimeter, E_T, for the 211 000 2-arm trigger events recorded at 900 GeV. The data show a rapid fall-off with a flattening towards higher energies as seen earlier by the UA1 and UA2 experiments [13]. The E_T distribution for the simulated Centauro events is also plotted in the figure, normalized to 1% of the data. Obviously, such a component in the data at the 1% level would be evident. A flattening of the E_T distribution is expected from QCD hard scattering and the observed behaviour could be attributed to such a process. A reliable subtraction of this contribution is however not possible for several reasons: uncertainties in the energy scale of the data lead to large (~ 100%) systematic uncertainties in measured jet cross sections, while the absolute normalization of theoretical calculations is also uncertain. Furthermore the calorimeter does not in general accept the full energy of jets, necessitating further uncertain corrections. In estimating the maximum possible contribution due to the Centauro phenomenon, we therefore neglect jet production and assume that the background from other processes extrapolates exponentially from lower values of E_T.

Upper limits for Centauro production were derived by examining the number of events with $E_T > 10$ GeV. We see 32 events in this region. An exponential fit to the E_T spectrum between 3 and 6 GeV predicts a background of 10±1 events. The net signal of 22±6 events corresponds, at 95% confidence level, to an upper limit on the fraction of extra events above 10 GeV of 1.5×10^{-4}. Dividing by the fraction (6.4%) of simulated Centauro events depositing more than 10 GeV in the calorimeter leads to an upper limit for Centauro production of 0.24% of the non single-diffractive cross section. The dependence of this upper limit on assumed $\langle p_T \rangle$ is shown as the dashed curve in fig. 3.

If Centauro events were present with anomalously low photon production one might hope that this would affect the longitudinal (depth) distribution of energy deposited in the calorimeter (this was the basis of UA1's Centauro study at $\sqrt{s}$ = 540 GeV [5]). We have therefore defined a quantity R:-

$$R = (E_{had} - E_{em})/(E_{had} + E_{em})$$

where E_{em} is the energy deposited in the electromagnetic part of the calorimeter (first 13.5 radiation lengths), and E_{had} is the remaining energy. Though electromagnetically induced showers will give values of R near -1, our Monte Carlo studies show that hadrons give a very broad distribution of R, with mean near zero. In particular, low energy charged hadrons may deposit most of their energy in the electromagnetic part of the calorimeter, due to ionization loss; furthermore, the very large annihilation cross-sections for low energy antibaryons also tend to result in shallow energy deposition. Since the small solid angle acceptance of the calorimeter means that only a few particles hit the calorimeter in each event, we find that R is not useful for identifying individual Centauro candidates. However, the average value of R can still be used to see whether any photon-depleted component exists at high E_T. Figure 2b shows $\langle R \rangle$ vs. E_T for 900 GeV data compared with normal and Centauro Monte Carlo predictions. The data seem to approach a constant value $\langle R \rangle \sim -0.35$ at high E_T, consistent with a normal Monte Carlo, whilst the Centauro simulation (lacking photons) gives $\langle R \rangle \sim 0$. Also plotted in the figure is a curve indicating the behaviour of $\langle R \rangle$ calculated assuming a mixture of normal and Centauro events when the latter are present at the fractional rate of 0.24%, corresponding to the upper limit at the 95% confidence level as mentioned above. Thus even our highest E_T point, on which the limits in fig.3 were based, appears to correspond to a "normal" particle composition, in which photons carry about one third of the transverse energy.

5. Analysis of the photon converter data

For part of the run, the photon converter was placed between the beam pipe and the upper chamber. Our algorithm which separates primary tracks from secondaries [7] was optimized in such a way that the correct number of primaries should be found. For the converter run, the configuration of material in the detector was different, and therefore the parameters of the algorithm were retuned. A further algorithm was then devised to search among the secondary tracks for likely electromagnetic showers, essentially looking for collimated groups of tracks, at least one of which should point near the primary vertex. This procedure was similar to our earlier analysis at 546 GeV [4].

Figure 4a shows the observed charged multiplicity, n_{ch}, versus the observed number of electromagnetic showers, n_{γ}, for the data taken at 900 GeV. The corresponding plot is shown for the standard UA5 Monte Carlo in fig.4b, showing good agreement with the data. Simulated events with Centauro characteristics (see section 3), also gave some "photons" when subjected to the same analysis, arising from misidentifications of primary tracks, for example. Figure 4c shows a scatter plot of n_{ch} versus n_{γ} for these simulated Centauro events. The distribution for data and Centauro Monte Carlo are very different, showing that no obvious population of Centauro events exists in the data. An upper limit for Centauro production was determined by comparing the number of events in the data and in the Centauro Monte Carlo for the region $n_{ch} > 60$ and $n_{\gamma} < 4$, indicated in fig.4 by the dashed lines. This region was chosen as one expects within it a negligible contribution from standard Monte Carlo events but a substantial contribution from Centauro events. For the simulated Centauros, the region contains 37% of the events, independent of the assumed $\langle p_T \rangle$. Of the 860 measured events recorded when the converter plate was in place, none lies within this zone. This gives an upper limit (at 95% c.l.) of three events, corresponding to 0.94% of non single-diffractive events.

To increase the fraction of possible Centauro events in the measured data sample, we took advantage of their expected higher p_T. A special sample of 88 events at 900 GeV with energy in the calorimeter greater than 3.2 GeV was measured, corresponding to an effective sample of 5500 unbiased events. Figure 4d shows the scatter plot of n_{ch} versus n_{γ} for these data. No depletion of n_{γ} is seen at large n_{ch}, and again no events pass the Centauro cuts described above.

Improved upper limits were calculated using the increased effective sample size. However, the efficiencies for events to pass the 3.2 GeV cut depend on the values of $\langle p_T \rangle$ used in the Centauro simulations. The resulting upper limits, plotted as a function of $\langle p_T \rangle$, are shown in fig.3.

6. Analysis of single-arm trigger data

The diffractive excitation and subsequent isotropic decay of a massive object will lead to an asymmetric event, and therefore generally to a 1-arm trigger in our detector. Our simulation of fireball-type Centauros gives a 1-arm trigger efficiency of ~ 90%. We have therefore investigated our 1-arm trigger data. The characteristics of these Centauro events should be high multiplicity coupled with a narrow rapidity distribution resulting from the isotropic decay ($\sigma_\eta \equiv \sqrt{\langle\eta^2\rangle - \langle\eta\rangle^2} \sim 0.8$). In contrast, normal diffractive events of high mass [14] appear to decay according to p_T limited phase space, giving broader distributions. Roughly speaking, if the region of acceptance between our backward trigger counters and the forward limit of the streamer chambers ($-2<\eta<4$) were filled uniformly, we should see $\sigma_\eta \sim 1.7$. Figure 5a shows a scatter plot of n_{ch} versus σ_η for 900 GeV 1-arm data, and fig.5b shows the corresponding plot for the simulated diffractive-type Centauros. The same box is drawn in each plot to guide the eye. There are clearly no events in the data corresponding to the simulated Centauro events, from which we derive an upper limit of 0.6% of 1-arm triggers (at 95% c.l.) to be Centauro-like. This corresponds to 0.06% of the inelastic cross section [8].

7. Summary and conclusions

No evidence for Centauro-like events has been found at the CERN SPS collider, either at $\sqrt{s}$ = 546 GeV [4,5] or in the present study at $\sqrt{s}$ = 900 GeV. In the latest analysis upper limits of 0.1 - 0.5% at 95% c.l. (depending on model assumptions) have been placed on Centauro production. This suggests that if the Centauro phenomenon exists, a threshold must occur between $\sqrt{s} = 900$ GeV and $\sqrt{s} = 1700$ GeV. Alternatively it could be that the Centauro events seen in the cosmic ray data are in fact normal events, whose apparently anomalous properties result from an extreme fluctuation of a kind to which the accelerator detectors might be less susceptible. On the other hand, if the observed Centauros were not the result of nucleon-nucleon collisions (for example if the projectile were some exotic object [15]) then accelerator based experiments could not be expected to see the phenomenon.

Acknowledgements

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Figure Captions

Fig.1 The data points represent the pseudorapidity distribution of Centauro I [3]. To the data (fig.9 of [3]) on observed showers we have applied an overall correction factor 1.5 based on the estimates for effects a) and b) quoted in table IV of [3]. Because of the energy threshold there are no data below η_{lab}= 8.5, and presumably the data points immediately above 8.5 would increase if this correction were applied. The dashed curve is the expectation for the isotropic decay of a fireball having the parameters quoted in table IV of [3]. The solid curve is our CPS interpretation which is equally compatible with the data.

Fig.2 (a) Distribution of E_T seen in the UA5 calorimeter. The curve represents our Centauro Monte Carlo with $\langle p_T \rangle = 1.45$ GeV/c, normalized to 1% of the data.

(b) Average value of R (= $(E_{had}-E_{em})/(E_{had}+E_{em})$) as a function of E_T for the data in fig.2(a). The solid curve is the expectation from the "normal" UA5 cluster Monte Carlo, and the dashed curve the expectation from the Centauro simulation. Both curves have uncertainties of about 0.05 at the high E_T end. A mixture of the two types of event results in the dot-dashed curve, when Centauro events have been taken to comprise 0.24% of all events, which is our upper limit on Centauro production assuming an $\langle p_T \rangle$ of 1.45 GeV/c.

Fig.3 Upper limits (at 95% c.l.) on Centauro production at 900 GeV, as functions of the assumed $\langle p_T \rangle$ of the Centauro event. The regions excluded by three different methods lie above the curves.

Fig.4 Plots of the number of observed charged particles, n_{ch}, against the number of observed photons, n_γ: (a) for 2-arm trigger data (860 events), (b) for our normal non single-diffractive Monte Carlo (860 events), (c) for the Centauro Monte Carlo (with $\langle p_T \rangle$ = 1.45 GeV/c; 250 events), and (d) for data with E_T>3.2 GeV in the calorimeter (88 events). All plots refer to $\sqrt{s}$ = 900 GeV. The area of each circle is proportional to the number of events in that bin. The dashed line is the cut described in the text, which would contain 37% of Centauros.

Fig.5 Plots of the number of observed charged particles, n_{ch}, against σ_{η}, (a) for 1-arm trigger data at $\sqrt{s}$ = 900 GeV and (b) for a diffractive-type Centauro Monte Carlo. The same dashed box is drawn in each figure to guide the eye. The area of each circle is proportional to the number of events in that bin.

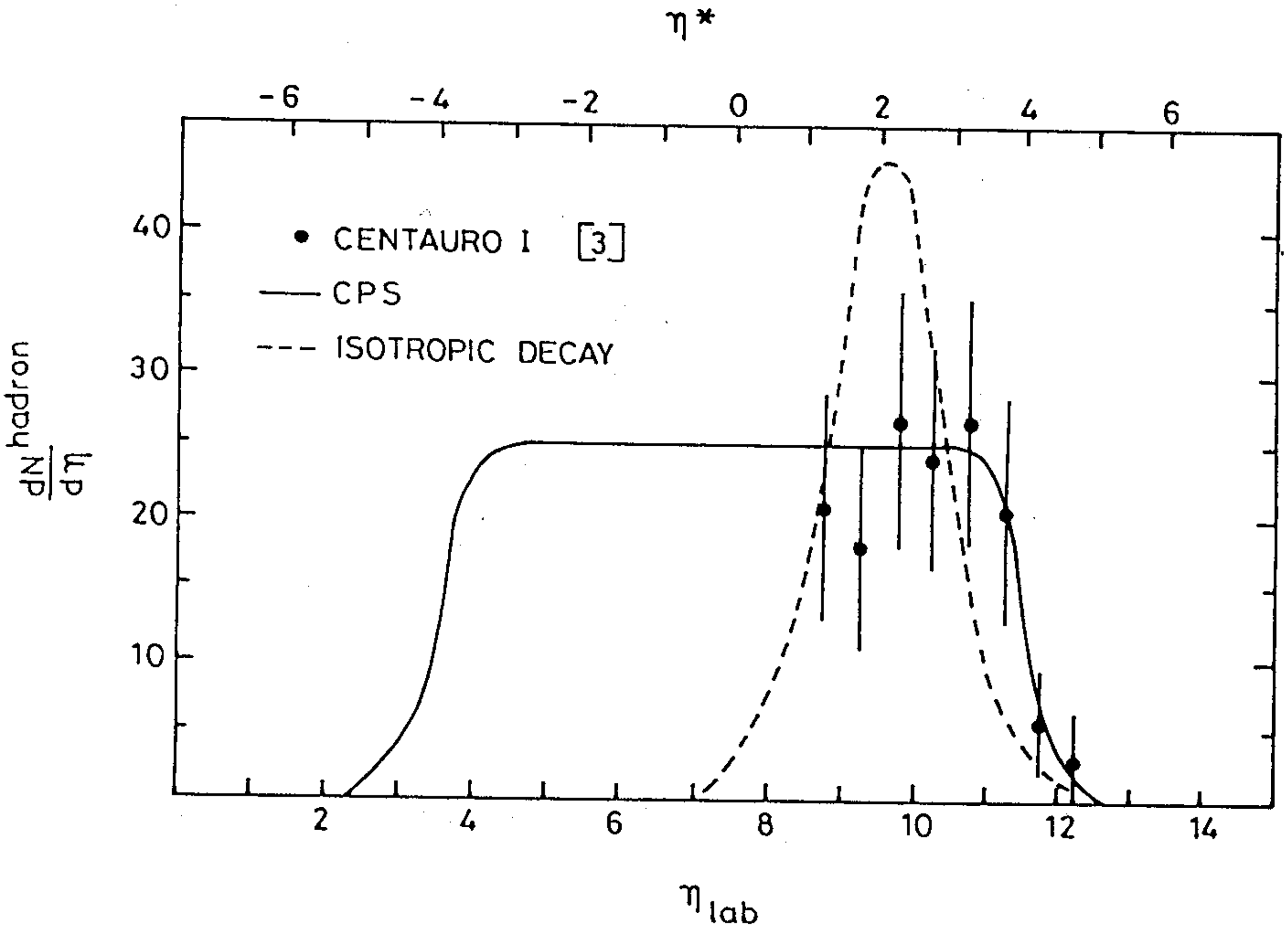
η*
-6
-4
-2
0
2
4
6
40
30
20
10
$\frac{dN^{hadron}}{d\eta}$
● CENTAURO I [3]
—— CPS
- - - ISOTROPIC DECAY
2
4
6
8
10
12
14
η_{lab}

FIG. 1

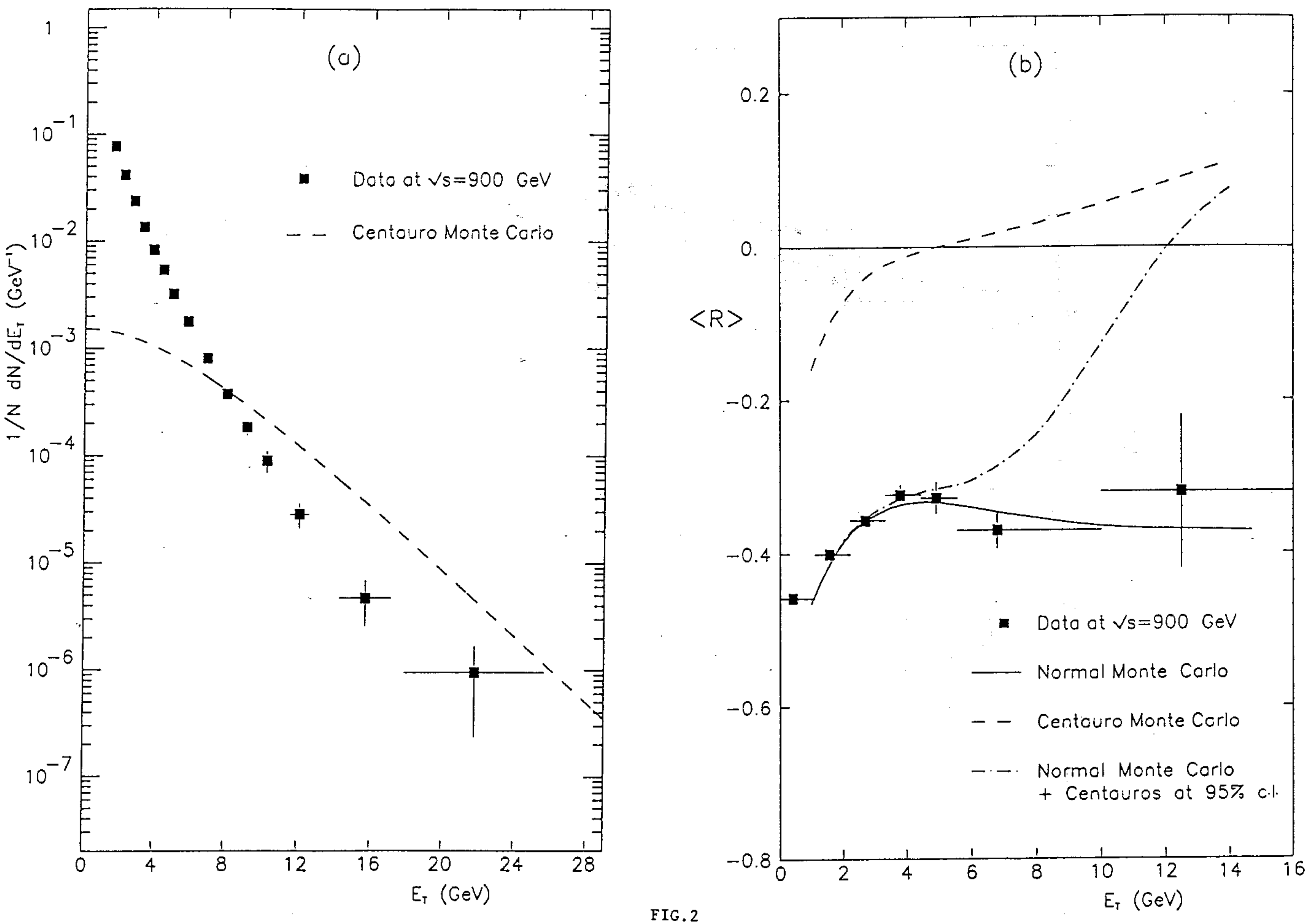(a)
Data at √s=900 GeV
Centauro Monte Carlo
1/N dN/dE_T (GeV^-1)
1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
0
4
8
12
16
20
24
28
E_T (GeV)
(b)
<R>
0.2
0.
-0.2
-0.4
-0.6
-0.8
0
2
4
6
8
10
12
14
16
E_T (GeV)
Data at √s=900 GeV
Normal Monte Carlo
Centauro Monte Carlo
Normal Monte Carlo
+ Centauros at 95% c.l.

FIG.2

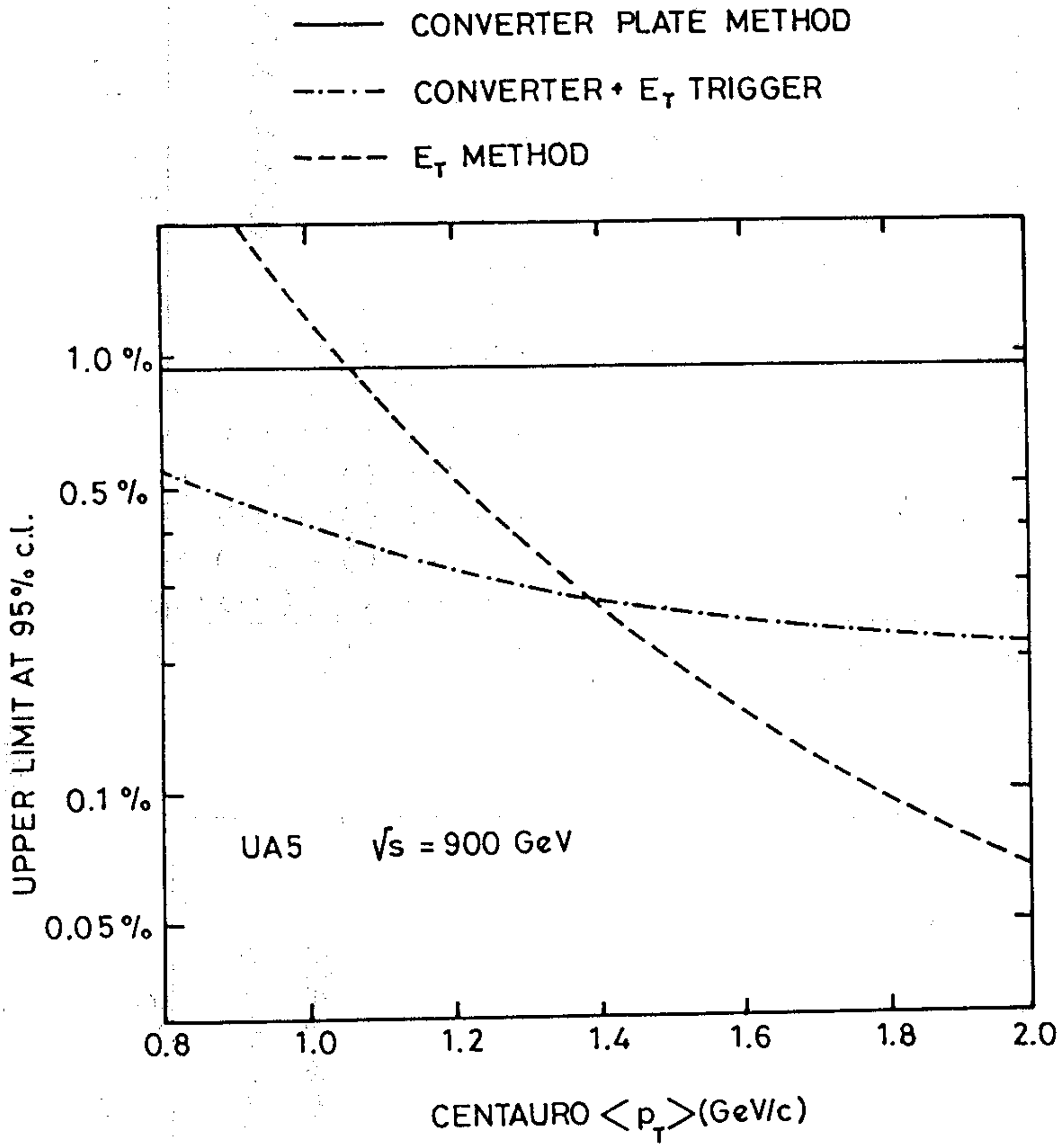
CONVERTER PLATE METHOD
CONVERTER + E_T TRIGGER
E_T METHOD
1.0 %
0.5 %
0.1 %
0.05 %
UPPER LIMIT AT 95% c.l.
UA5
$\sqrt{s}$ = 900 GeV
0.8
1.0
1.2
1.4
1.6
1.8
2.0
CENTAURO $\langle p_T \rangle$ (GeV/c)

FIG. 3

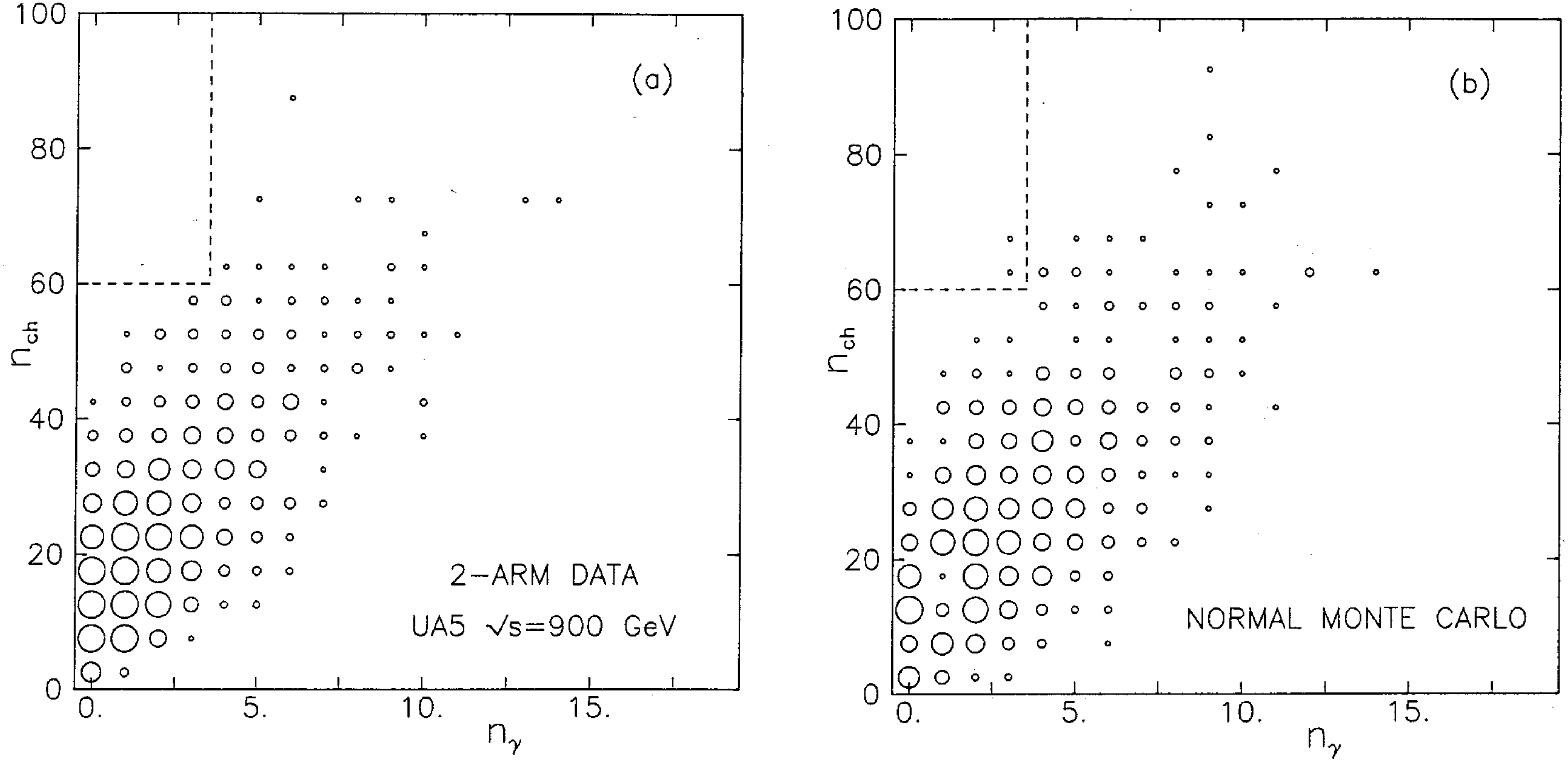
(a)
2-ARM DATA
UA5 √s=900 GeV
n_{ch}
n_γ
0
20
40
60
80
100
0.
5.
10.
15.
(b)
NORMAL MONTE CARLO
n_{ch}
n_γ
0
20
40
60
80
100
0.
5.
10.
15.

FIG.4

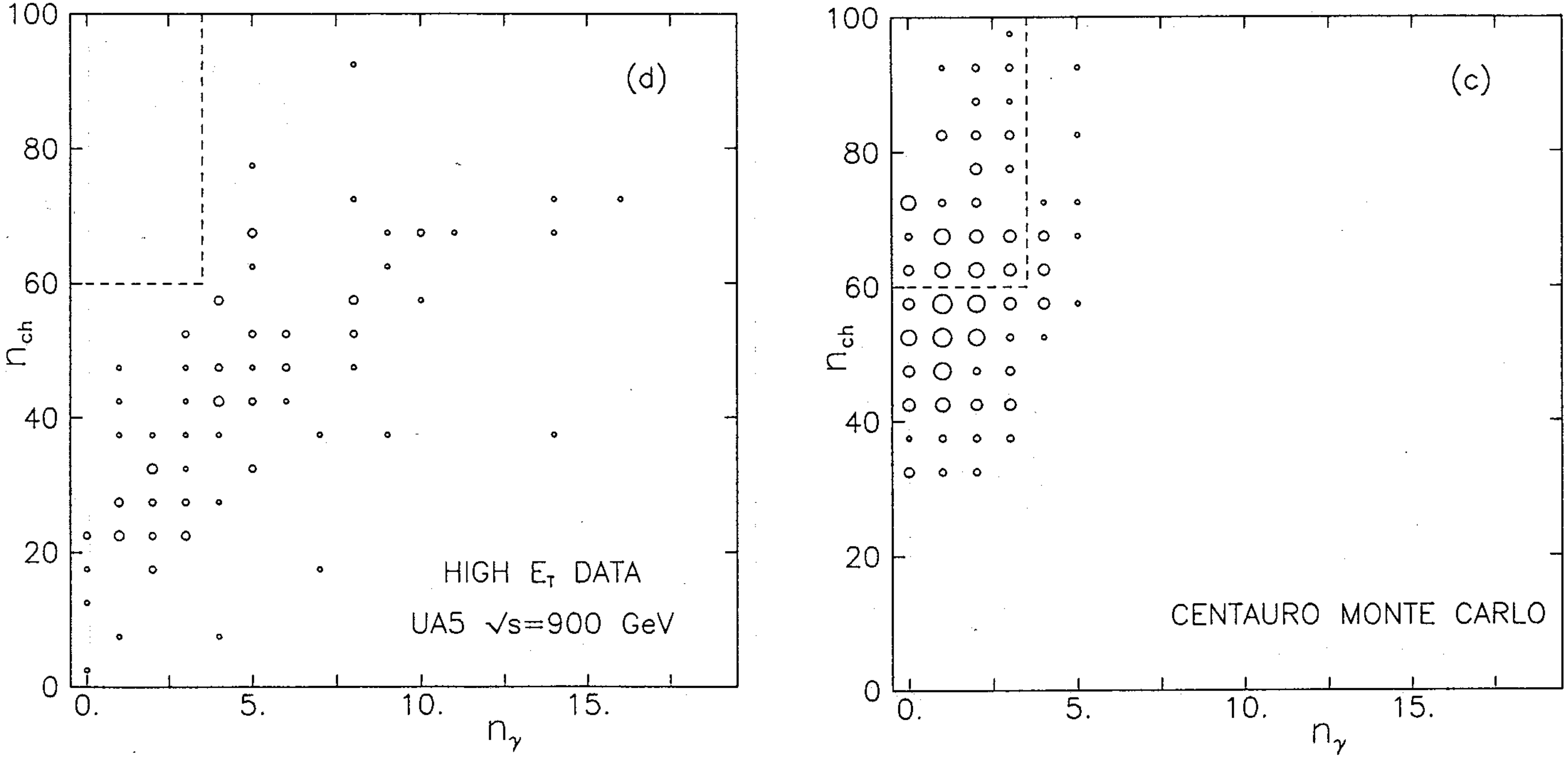
(d)
HIGH E_T DATA
UA5 $\sqrt{s}=900$ GeV
n_{ch}
n_γ
0
20
40
60
80
100
0.
5.
10.
15.
(c)
CENTAURO MONTE CARLO
n_{ch}
n_γ
0
20
40
60
80
100
0.
5.
10.
15.

FIG.4

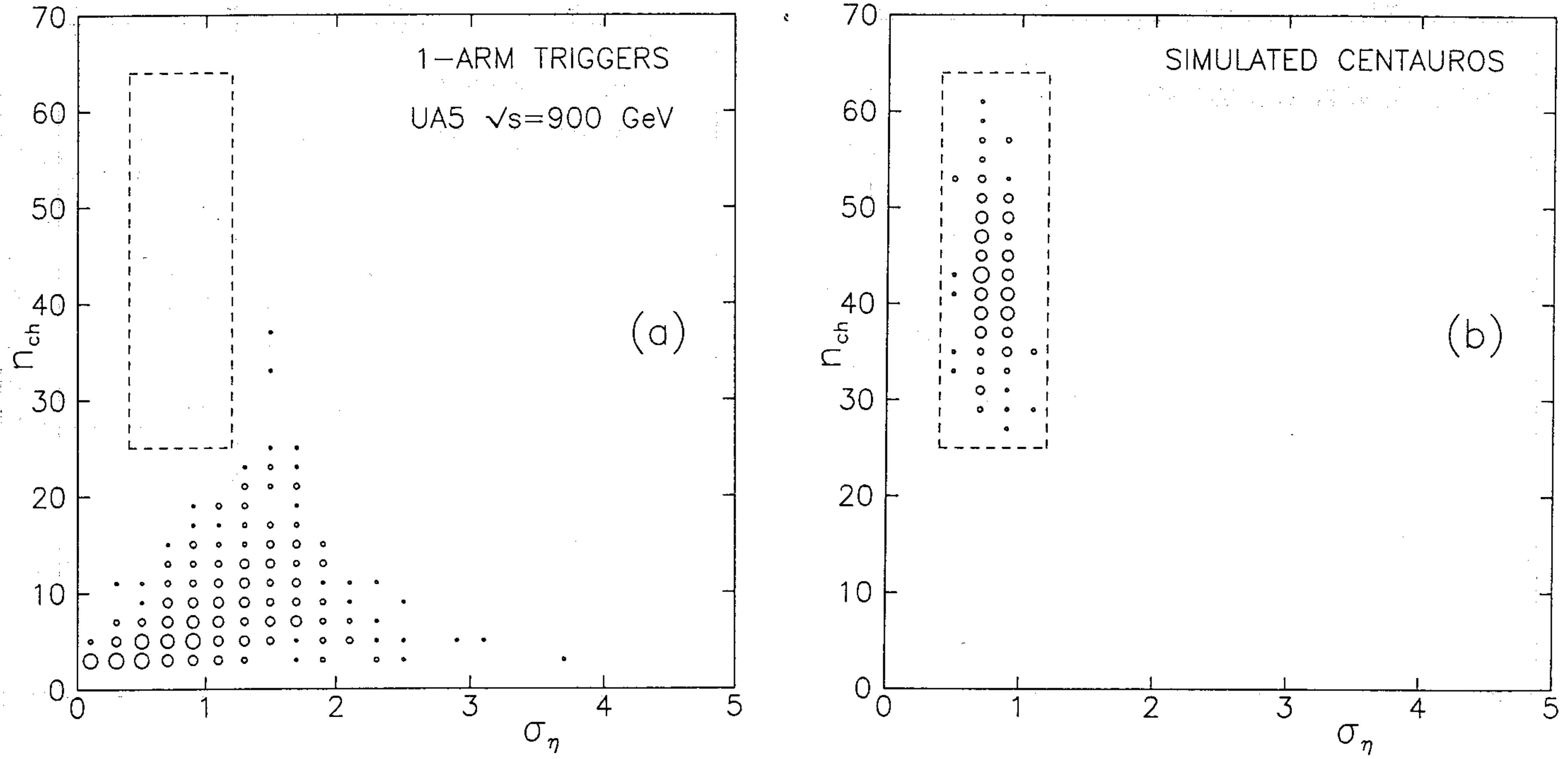
1-ARM TRIGGERS
UA5 √s=900 GeV
(a)
SIMULATED CENTAUROS
(b)
n_{ch}
σ_η
0
10
20
30
40
50
60
70
0
1
2
3
4
5

FIG.5