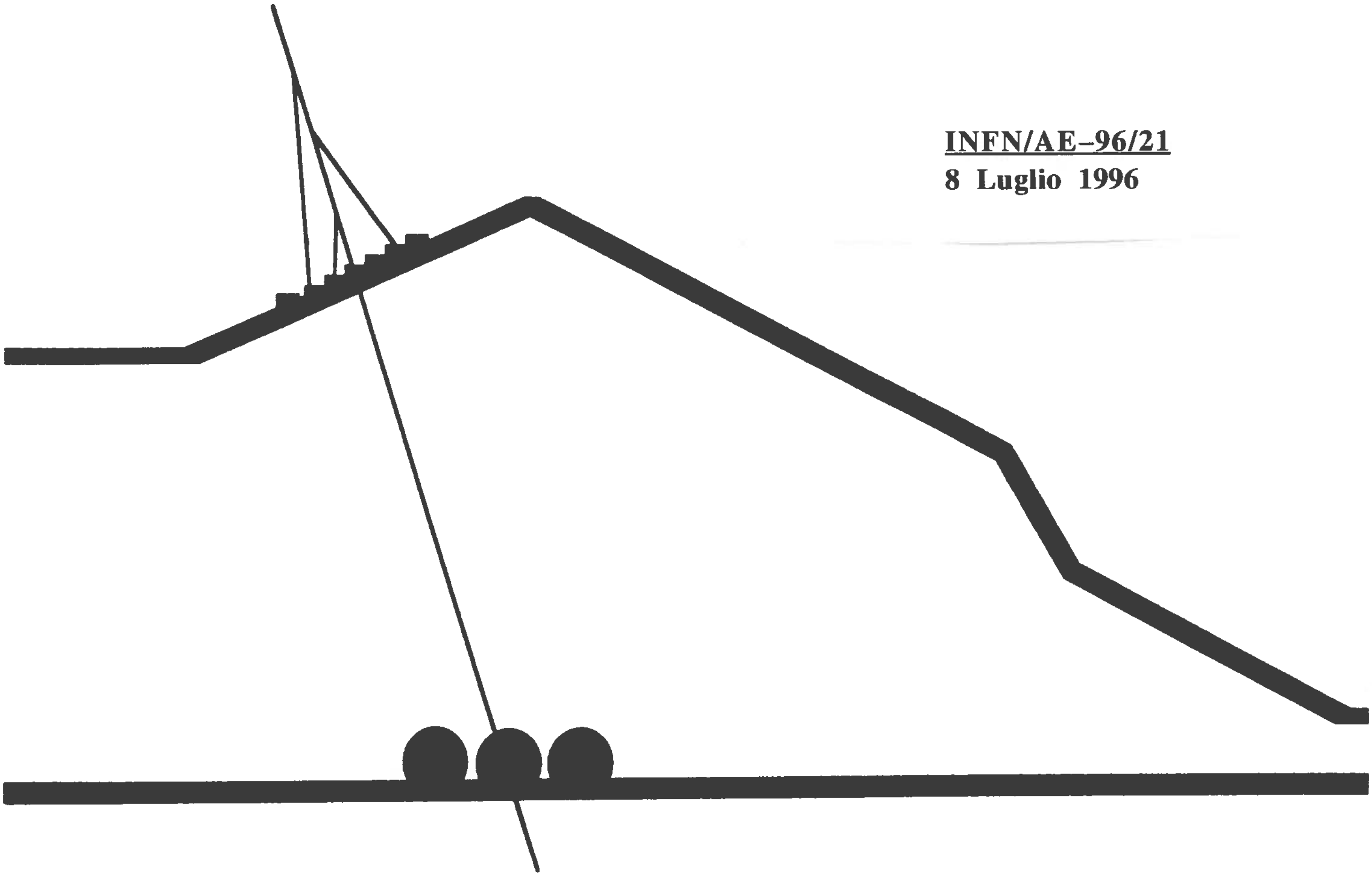

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EAS-TOP Collaboration

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A LIMIT TO THE RATE OF ULTRA HIGH ENERGY γ–RAYS IN THE PRIMARY COSMIC RADIATION

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Abstract

An upper limit to the flux of Ultra High Energy (UHE) γ-rays in the primary cosmic radiation is obtained through the data of the electromagnetic and the muon detectors of the EAS-TOP Extensive Air Shower array (Campo Imperatore, National Gran Sasso Laboratories, atmospheric depth $810\,\mathrm{g\,cm^{-2}}$). The search is performed by selecting Extensive Air Showers (EAS) with low muon content. For EAS electron sizes $N_e > 6.3 \cdot 10^5$, no showers are observed with the core located inside a fiducial area and no muons recorded in the 140 m^2 muon detector, during a live time of 8440 h. The 90% c.l. upper limit to the relative intensity of γ-ray with respect to cosmic ray (c.r.) primaries is $I_\gamma/I_{\mathrm{c.r.}} < 7.3 \cdot 10^{-5}$, at primary energy $E_0 \geq 1. \cdot 10^{15}$ eV: this limit is lower than reported in previous measurements.

1 Introduction

The rate of Very High Energy (VHE, $10^{11} < E_0 < 10^{13}$ eV) and Ultra High Energy (UHE, $E_0 \geq 10^{13}$ eV) γ-rays in the primary cosmic radiation, and hence the magnitude of the diffuse flux of VHE-UHE photons, is an open problem in astrophysics. Due to their low fluxes, VHE and UHE primary photons cannot be detected through the limited areas of satellite and balloon borne experiments. The required large collection areas ($> 10^5$ m^2) can be provided by the detection of the secondary particles that primary cosmic rays produce in the interaction with the atmosphere (Extensive Air Shower, EAS). EAS are characterized by the total electron number, i.e. the shower size N_e ($N_\mathrm{e} \approx 10^{-10}\, E_0$ [eV] at sea level, $N_\mathrm{e} \approx 10^{-9}\, E_0$ [eV] at mountain altitude) and by the total muon number N_μ ($N^h_\mu / N^\mathrm{h}_\mathrm{e} \approx 10^{-1} \div 10^{-2}$ in hadron initiated showers). Muons are generated from the decay of charged pions and kaons, which, in hadronic showers, are produced in nucleus-nucleus interactions, while in photon showers only in photoproduction processes. The ratio between the cross sections of photoproduction and of nucleus-nucleus interaction processes is $\approx 10^{-3}$ (experimentally confirmed up to an equivalent laboratory energy of $E_\gamma \approx 2.\cdot 10^{13}$ eV [1]) resulting in $< N^\gamma_\mu > / < N^\mathrm{h}{}_\mu > \approx 3.\cdot 10^{-2}$. Thus the usual criterion for selecting γ-ray primaries from the hadronic background is by identifying 'μ-poor' EAS. This method was proposed in early sixties [2–4], its main limitations being due to the extent of fluctuations in hadron-initiated showers, and to the aforementioned small number of muons N_μ.

The existence of *μ-poor* showers was reported by the Polish-French collaboration [5,6] and by the Bolivian Air Shower Joint Experiment [7–9] that respectively derived an intensity of γ-ray relative to cosmic ray (c.r.) primaries $I_\gamma / I_\mathrm{c.r.} \approx 6.\cdot 10^{-3}$ for $N_\mathrm{e} \approx 6.\cdot 10^5$ (at sea level) and $I_\gamma / I_\mathrm{c.r.} \approx 5.\cdot 10^{-4}$ for $5.\cdot 10^5 < N_\mathrm{e} < 5.\cdot 10^6$ (at 5200 m a.s.l.). The Tien Shan air shower array [10] through

the selection of muon and hadron-poor showers, reported a γ-ray intensity $I_\gamma(> 4. \cdot 10^{14}\text{eV}) = (3.4 \pm 1.2) \cdot 10^{-13}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$, i.e. $I_\gamma/I_{\text{c.r.}} = (1.0 \pm 0.3) \cdot 10^{-3}$. More recently, upper limits to the isotropic flux of γ-rays have been set, based upon (i) the selection of μ-poor showers [11]: $I_\gamma/I_{\text{c.r.}} < 4.3 \cdot 10^{-3}$ for $E_0 > 2. \cdot 10^{14}$ eV and $I_\gamma/I_{\text{c.r.}} < 4.8 \cdot 10^{-4}$ for $E_0 > 1. \cdot 10^{15}$ eV (90% c.l.); (ii) the data on the spectrum of the electromagnetic component in atmosphere recorded by emulsion chambers at various depths [12]: $I_\gamma/I_{\text{c.r.}} < 10^{-3}$ for $5. \cdot 10^{12} < E_0 < 1. \cdot 10^{15}$ eV (90% c.l.) (see also the discussion in ref. [13]); (iii) the study of the EAS Cherenkov light lateral distribution [13]: $I_\gamma/I_{\text{c.r.}} < 10.3 \cdot 10^{-3}$ for $6.5 \cdot 10^{13} < E_0 < 1.6 \cdot 10^{14}$ eV and $I_\gamma/I_{\text{c.r.}} < 7.8 \cdot 10^{-3}$ for $8. \cdot 10^{13} < E_0 < 2.0 \cdot 10^{14}$ eV (90% c.l.).
Two main sources of diffuse flux of UHE γ radiation are expected:

- a) the first one is due to the production of UHE photons by the interactions of cosmic rays with the interstellar gas in the disk of the Galaxy (as observed in the 100 MeV energy range) [14,15]: the predicted integral intensity, peaked at the galactic disk, is $I_\gamma(E_0 > 1. \cdot 10^{14}\ \text{eV}) = 6.6 \cdot 10^{-13}\text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$, corresponding to $I_\gamma/I_{\text{c.r.}} \approx 6.4 \cdot 10^{-5}$, with a steepening of the spectrum at $E_\gamma > 5. \cdot 10^{14}$ eV, due to the absorption of UHE photons on microwave radiation;
- b) the second source is provided by the collisions of extragalactic cosmic rays with the 2.7 K cosmological background radiation: this results in an isotropic flux of secondary photons with a characteristic energy of $\approx 1. \cdot 10^{14}$ eV, at a level of $\lesssim 10^{-4}$ of the c.r. flux, under the hypothesis that c.r. of energy $> 10^{18}$ eV are of extragalactic origin, uniformly distributed over cosmological distances [14,16].

The measurement of the diffuse isotropic γ-ray flux due to the source b), and of its spectrum, would therefore provide information on the UHE extragalactic cosmic ray component. Moreover, this flux represents a background for experiments searching for the γ-ray enhancement from the direction of the galactic disk (source a), and therefore has to be known.

Furthermore, there can be other sources of diffuse isotropic γ-rays of unknown or speculative origin. Any mechanism of production of UHE particles is indeed accompanied by production of pions and then γ-rays, especially through electromagnetic cascades. An example is given by cosmic strings [17,18].

In this paper we present an upper limit to the diffuse isotropic flux of primary γ-rays, obtained at the EAS-TOP experiment, through the combined data of the electromagnetic and muon detectors, by means of a selection on the number of detected muons, N_μ^{det}. The selections are effective at $E_0 \approx 10^{15}$ eV (i.e. still higher than the typical energies expected for γ-rays produced by the interactions of the extragalactic cosmic ray component); at these energies, the present result lowers the existing upper limits, and provides an upper limit to the fluctuations of the muon number in EAS produced by hadronic primaries.

2 The detectors

The EAS-TOP array is located at Campo Imperatore, Italy (2005 m a.s.l., atmospheric depth 810 g cm^{-2}, lat. 42.5^o N, long. 13.5^o E, National Gran Sasso Laboratories). The data under consideration are from:

- the electromagnetic detector [19,20]: 35 scintillator modules (10 m^2 each), distributed over an area of $\approx 10^5$ m^2. The events selected for the present analysis are the so called 'internal' showers, for which at least six detectors have been fired and the highest particle density has been recorded by a module not located at the edges of the array (the trigger reaches 50% efficiency for primary γ-rays at $N_e \approx 4. \cdot 10^4$, i.e. $E_0 \approx 1.2 \cdot 10^{14}$ eV). For these events (whose rate is $\nu \approx 1.5$ Hz), the EAS core location (x_c, y_c) and the shower size (N_e, in units of vertical minimum ionizing particles) are determined by means of a fit of the number of particles recorded by each scintillator module to the Nishimura-Kamata-Greisen formula [21]. The arrival direction ψ is obtained from the times of flight among the detectors.

The accuracies in the reconstruction of the EAS parameters, at $N_e > 10^5$, are the following [19,20]:
$\sigma_{N_e}/N_e = 0.1$
$\sigma_{x_c}=\sigma_{y_c} = 5$ m
$\sigma_\psi = 0.5 \pm 0.1^o$
- the muon detector [22,23], of dimensions $12\times12\,\mathrm{m}^2$: 9 layers of iron absorber 13 cm thick, interleaved by sensitive layers made of 3 planes of streamer tubes ($3\times3\times1200$ cm^3 each), two of them operating in streamer mode for muon counting and tracking (the muon energy threshold for vertical incidence is $E_{\mu\mathrm{th}} \approx 1$ GeV). The X coordinate of the muon track is obtained by the signals of the anode wires, and the Y coordinate by the induced signals on the strips orthogonal to the wires. Sixteen layers of streamer tubes are used for the reconstruction of the muon track, which is defined by the alignment of at least 6 wires and 6 strips hits. For the present analysis, the number of muons N_μ^{det} is counted on the wires view (X). The probability for a muon track to be lost is < 2%, therefore not affecting the analysis. The rate f_{ch} of muon chance coincidences has been measured experimentally, thus including all instrumental effects: $f_{\mathrm{ch}} = 0.16$.

3 The analysis and the results

We have analyzed $S_{\mathrm{tot}} = 4.5 \cdot 10^7$ 'internal' events, recorded in 8440 h of effective running time. Out of these, $S = 814540$ events have been selected with zenith angle $\theta < 35^o$, and with distance between the EAS core and the μ detector R <80 m. The ranges of θ and R are selected in order to operate at nearly constant primary energy threshold and to maximize the number of events without affecting the μ detection efficiency. The distributions of the number of detected muons N_μ^{det} for two shower size thresholds are shown in Fig. 1.

The number of recorded showers, S, and of showers characterized by no detected muons, $S_{0\mu}$, are shown in Table 1 for different threshold values of N_e. In each interval, $S_{0\mu}$ can be used to ob-

tain an upper limit to the rate of candidate primary γ-rays. In particular, (see also Fig. 1), the most significant information is provided for $N_e > 6.3 \cdot 10^5$ with $S_{0\mu}$=0 and S=30718.
We have shown in a previous paper [23] that the measured muon lateral distributions and the average number of muons N_μ are those expected from the c.r. primary flux. Concerning γ-ray initiated showers, the expected number of muons has been obtained through a simulation based on the EGS4 code [24] and including the μ detector response. The same simulation provides the conversion between N_e and the primary energy E_0, including the transition effect in the scintillators. The primary photon energies are extracted on a $E^{-2.7}$ differential spectrum, as the observed cosmic-ray one. Applying to the simulated showers the same selection criteria as to the experimental data sample, i.e. $\theta < 35^o$ and R <80 m, we determine the fraction of events giving zero muons in the μ detector, i.e. the efficiency ϵ_γ in the retention of primary γ-rays, when the N_μ^{det}=0 cut is applied. ϵ_γ depends on the considered range of N_e. Taking into account the contamination due to the muon chance coincidence rate, the resulting efficiency for the chosen criterium is $\eta_\gamma = \epsilon_\gamma \cdot (1 - f_{\rm ch})$.
In case of $S_{0\mu}$=0, as for $N_e > 6.3 \cdot 10^5$, the 90% c.l. upper limit to the number of candidate γ-rays with respect to cosmic rays events is given by:

$$\frac{I_\gamma}{I_{\rm c.r.}} < \frac{S_{90}}{\eta_\gamma S} \qquad (1)$$

where S_{90}=2.7, including the muon chance contamination. This holds for fixed shower size N_e; to convert it to fixed primary γ-ray energy, the ratio between the primary energies giving the same shower size N_e in case of photon (E_γ) and c.r., i.e. proton, initiated showers ($E_{\rm c.r.}$), has to be taken into account. The upper limit is then given by:

$$\frac{I_\gamma}{I_{\rm c.r.}} < \frac{S_{90}}{\eta_\gamma S} \left(\frac{E_{\rm c.r.}}{E_\gamma} \right)^{-\gamma+1} \qquad (2)$$

where γ=2.7 is the differential spectral index of the cosmic-ray spectrum, and $E_{\text{c.r.}}/E_\gamma \approx 1.6$ is obtained for our data through a simulation based on the CORSIKA code [25].
For $\text{N}_e > 6.3 \cdot 10^5$, i.e. for $E_0 > 1. \cdot 10^{15}$ eV (E_0 being calculated at the mean zenith angle $< \theta >= 20^o$), from expression (2), with $\epsilon_\gamma = 0.59$, we obtain:

$$\frac{I_\gamma}{I_{\text{c.r.}}} < 7.3 \cdot 10^{-5}.$$

For $\text{N}_e > 5. \cdot 10^5$ (i.e. $E_0 > 8.7 \cdot 10^{14}$ eV), eq. 2 still holds, with $S_{90} = 6.3$ and $\epsilon_\gamma = 0.63$, giving:

$$\frac{I_\gamma}{I_{\text{c.r.}}} < 1. \cdot 10^{-4}$$

The upper limits to the integral intensity of γ-rays, using the c.r. primary spectrum of ref. [26], are

$$I_\gamma(> 8.7 \cdot 10^{14} \text{ eV }) < 1.8 \cdot 10^{-14} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

$$I_\gamma(> 1. \cdot 10^{15} \text{ eV }) < 1. \cdot 10^{-14} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

4 Conclusions

By means of the combined data of the electromagnetic and muon detectors of the EAS-TOP experiment, a limit to the diffuse flux of UHE γ-rays in the primary cosmic radiation is set, through the selection of Extensive Air Showers characterized by no muons recorded in a 140 m^2 detector.
90% c.l. upper limits to the ratio of the γ-ray to the cosmic-ray flux are derived: for $E_0 > 8.7 \cdot 10^{14}$ eV and $E_0 > 1. \cdot 10^{15}$ eV we obtain $I_\gamma/I_{\text{c.r.}} < 1. \cdot 10^{-4}$ and $I_\gamma/I_{\text{c.r.}} < 7.3 \cdot 10^{-5}$ respectively.
These results:

- a) provide an upper limit, lower than the existing ones, to the flux of cosmic diffuse UHE γ-rays in the considered energy range;

- b) establish an upper limit to the fluctuations of the muon content in hadronic showers showing that, at least at such energies, the measurement of a $\lesssim 10^{-4}$ μ-poor effect due to primary gamma-rays would be possible;
- c) set a limit to the backgroud rate of μ-poor showers in the search for the galactic disk enhancement.

ACKNOWLEDGMENTS
The authors wish to express their thanks to the director and the staff of the National Gran Sasso Laboratories for their constant support, as well as to C. Barattia, R. Bertoni, M. Canonico, G. Giuliani, A. Giuliano and G. Pirali for their precious technical assistance. A stimulating discussion with V.S. Berezinsky is gratefully acknowledged.

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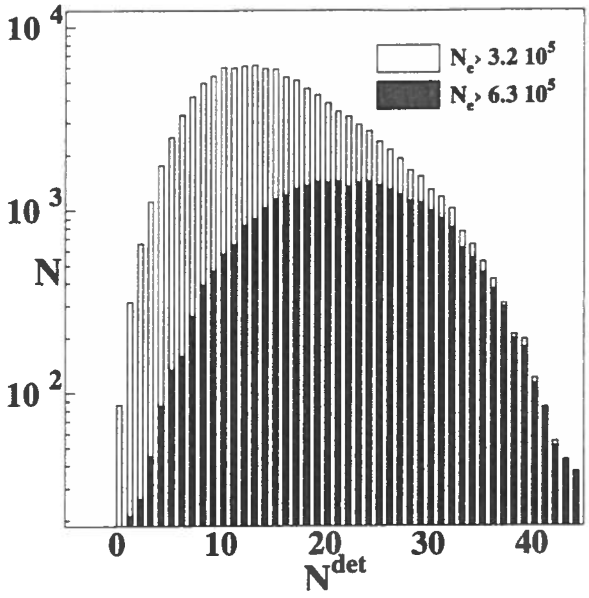

Fig. 1. Distributions of the number of detected muons N_μ^{det} for $N_e > 3.2 \cdot 10^5$ and $N_e > 6.3 \cdot 10^5$.

N_e	S	$S_{0\mu}$
$> 1.0 \cdot 10^5$	814540	14499
$> 1.3 \cdot 10^5$	555743	5713
$> 1.6 \cdot 10^5$	374917	2059
$> 2.0 \cdot 10^5$	251728	730
$> 2.5 \cdot 10^5$	168557	266
$> 3.2 \cdot 10^5$	111999	86
$> 4.0 \cdot 10^5$	74204	25
$> 5.0 \cdot 10^5$	48238	3
$> 6.3 \cdot 10^5$	30718	0

Table 1
Results of the search for μ-poor events at different threshold values of N_e: the total number of recorded showers, S, and of showers with no detected muons, $S_{0\mu}$, are shown.

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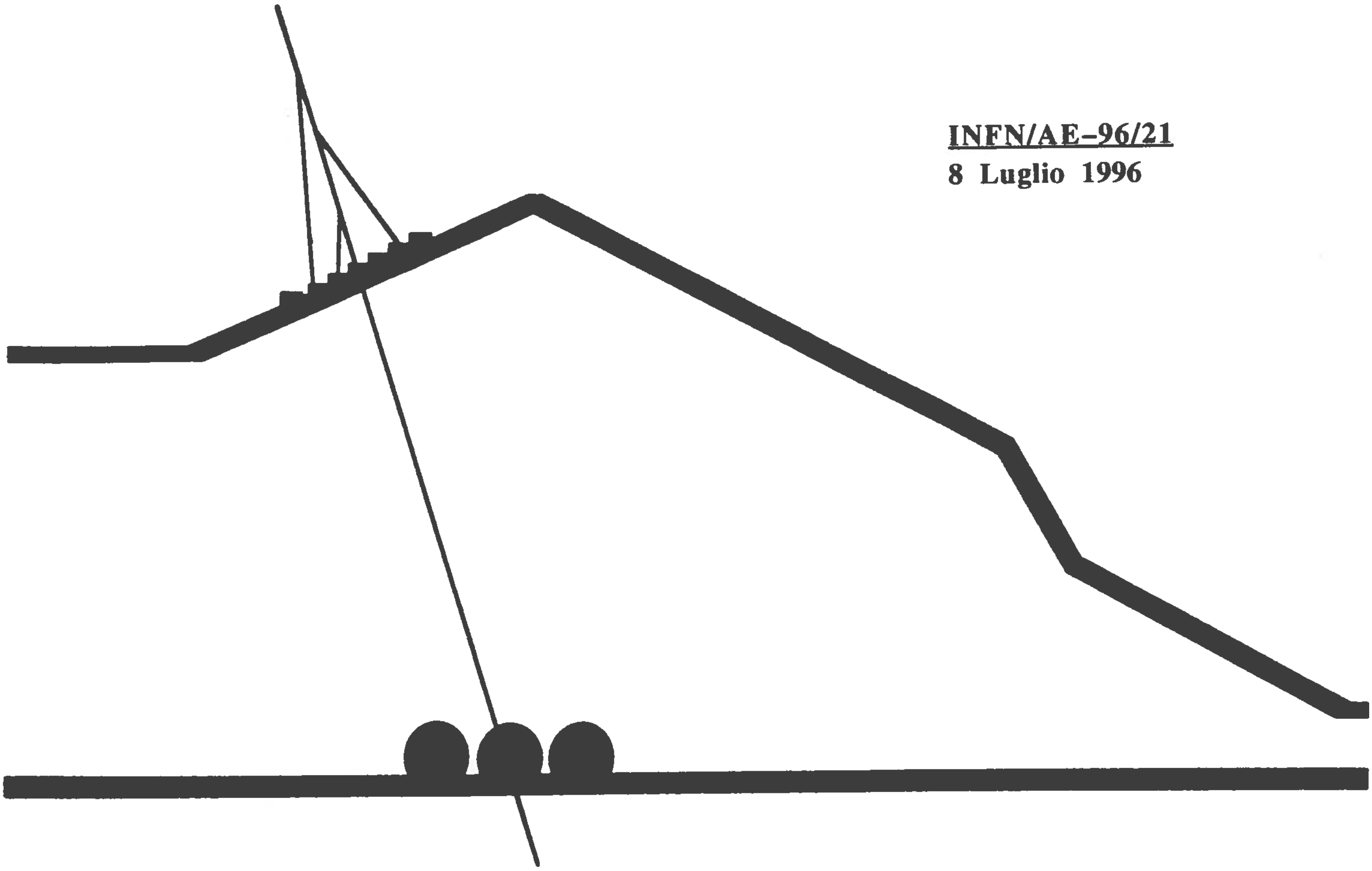

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