Cosmic ray composition and inelasticity uncertainties unveiled by a full acceptance detector at the LHC

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(June 1997)

We discuss an intrinsic ambiguity on the interpretation of results on cosmic-ray physics, related to the impossibility of deducing two unknowns: the chemical composition of primary cosmic rays and the dynamics of particle interactions in the fragmentation region, based only on a single measurement. We indicate how the operation of a full acceptance detector at the CERN Large Hadron Collider, like the FELIX detector, can overcome the uncertainties, decide in favor of a particular model and give the key to answer the long lasting questions concerning the composition and origin of the cosmic radiation, up to the highest measured energies.

I. INTRODUCTION

Since the identification of cosmic rays by Viktor Hess, during his balloon flights in 1911-12, there have been a series of important discoveries related to elementary particle physics, through cosmic-ray experiments. Some examples are the discovery of positrons (1932), muons (1936), pions (1947), kaons and lambdas (1949-51), sigma and cascade particles (1952-53). Then came the accelerator era. Previous cosmic-ray discoveries were confirmed in laboratories. More than that, the technology achieved in laboratory produced beams with energies comparable to those available in cosmic rays, with the advantage of higher resolution in energy and direction. For that reason, the interest in cosmic rays moved to problems on their origin and their propagation through the interestellar medium. Nevertheless, over the past decades, cosmic-ray physics has accumulated a number of surprising experimental evidences, which have defied explanation and are known as the "cosmic-ray anomalies" [1–3].

Some of those anomalous observations can possibly be understood in the frame of known physics, while some others may truly be a hint of new physics. Deciding between usual and unusual phenomena requires:
i) clear understanding of the anomalous event and of its measurement procedures;
ii) in depth investigation of the dynamics of high energy interactions, mainly in the very forward region of the phase space; and finally,
iii) a comprehensive model to describe the experimental observations - which may or may not indicate the presence of new physics.
Unfortunately, the three steps outlined above - state of the problem, state of the underlying physics and state of the explanation - does not always come together.

In the discussion to follow, we attempt to address the status of those requirements, considering a specific case in the row of cosmic-ray ambiguities. Namely, we draw attention to the impossibility of deducing two unknowns, the chemical composition of primary cosmic rays and the dynamics of particle interactions, from a single measurement. Accordingly, we show how the operation of a full acceptance detector at the Large Hadron Collider (LHC) can overcome present uncertainties and help answer some of the most long standing puzzles in cosmic-ray physics.

II. COSMIC-RAY ANOMALIES

Recent experiments revealed some surprising and unexpected results [3]. Some of the occurrences in this new set of challenging observations are the inconsistent relation between detected energy and the number of electrons among air showers and emulsion chamber events (HADRON experiment and Japanese Emulsion Chamber Collaboration); the anomalous hadronic mean-free-path, called the long-flying-component (Tien-Shan experiment); the anomalous heavy flavor production (JACEE Collaboration); and, the short attenuation length of secondary hadrons (Chacaltaya-Pamir Collaboration). In addition, there are other unsolved questions, posed a long time ago. They have been measured, confirmed and still sustain the polemics alive. For example, there is a collection of exotic events, such as Centauros, Anti-Centauros, Mini-Centauros, Mini-Clusters, Chirons, Geminions and Halo-Events - detected by the Brazil-Japan Collaboration or JACEE. For each one there is a particular morphological description, and extensive analyses - but all of them have one fact in common: they have not received a satisfactory explanation for over 10 years.

Among the most intriguing questions, there is the problem of the origin and composition of primary cosmic rays, up to the highest measured energies [4,5], which has important astrophysical and cosmological implications [6,7]. The overall spectrum of high energy cosmic rays (above 1 TeV) has a known structure [8], with a significant change in slope around a PeV (10^3 TeV), a region in the spectrum called the "knee", and again a change around 10^4 PeV, the "ankle". It is believed that those breaks in the spectrum indicates the presence of different mechanisms of particle acceleration in the interstellar medium. For energies below the "knee" it is possible to obtain a direct observation of primary particle interactions, from satellite or balloon borne emulsion chamber experiments [9]. The steepness of the flux and the limited size and duration of the exposures impose a constrain on obtaining data at higher energies. Therefore, in the region of the "knee" and above, information on the energy spectrum and the composition has to be inferred by indirect means - through air shower experiments at sea level and mountain altitudes, using large area detectors for long periods of time [10], or through multiple muon events, recorded by large volume deep underground detectors [11,12].

The connection between the nature of the primary particle and the actual experimental observation - so far away from the top of the atmosphere - requires a detailed understanding of particle interactions at very high energies and at forward scattering angles. Since there is still no information available from accelerator based experiments on this domain, we are faced with an intrinsic ambiguity on the interpretation of the results obtained through those cosmic-ray experiments. The ambiguity is governed by our poor understanding of two basic elements: the dynamics of multiparticle production, which dictates the behavior of the inelasticity K, and the composition of the primary cosmic radiation, which translates itself through the average mass number A of the primary particles. Therefore, from now on, we refer to this problem as the "Inelasticity K - Mass Number A - Uncertainty", or simply KAU.

III. THE KAU-PROBLEM

To better appreciate the extension of the KAU-problem, we consider, as an example, two sample models of particle production, investigating the constrains on the choice of the primary composition posed by the attempts to describe different sets of cosmic-ray data. We start by defining their proper parametrizations of the rapidity density distribution of charged pion production, dN/dy.

Model 1:

Feynman Scaling Violation with Proton Primary.

Based on the adjustment of accelerator data at center-of-mass system energies $\sqrt{s}$ = 53, 200, 546 and 900 GeV, from the UA5 Collaboration [13], and $\sqrt{s} = 630$ GeV from the UA7 Collaboration [14], Ohsawa and Sawayanagi obtained the phenomenological distribution given by [15]

$$\frac{dN}{dy} = x\frac{dN}{dx} = \frac{5}{3}\left(\frac{s}{s_o}\right)^{\alpha}\left[1-\left(\frac{s}{s_o'}\right)^{\alpha'} x\right]^4 , \qquad (1)$$

where y is the rapidity of the secondaries and the Feynman variable x is given by the ratio of the energy E of the secondary particle to the incident energy E_0. The parameters in Eq. (1) are $\alpha = 0.11$, $\alpha' = 0.17$, $s_o = 6.3\times10^2$ GeV^2 and $s_o' = 1.8\times10^3$ GeV^2. Under this model, which clearly violates Feynman scaling in the forward region, the average inelasticity $\langle K\rangle$ is a decreasing function of energy.

Assuming a proton primary spectrum at the top of the atmosphere (taking $\langle A\rangle = 1$), it is possible to describe experimental data obtained in large emulsion chambers at different atmospheric altitudes, using rigorous analytical solutions of the diffusion equations for the hadronic cascade therein produced. Consider, for example, the visible-energy spectrum of charged hadrons in air showers, detected at Mt. Fuji [16] (atmospheric depth of 650 g/cm^2), depicted in Fig. 1. The dashed line represents the calculation [17] adopting Eq. (1) as the multiparticle production spectrum, and $\langle A\rangle = 1$. The same model can be applied to quite a different situation. Primary protons or leading nucleons produced in the first interaction with the nucleus of air can propagate deeper into the atmosphere to produce very energetic showers. Those are detected in high altitude emulsion chamber experiments as a bundle of well collimated particles, called "family events". Fig. 2 shows the integral energy spectra of particles for the family Ursa Maior [18], detected by the Brazil-Japan Collaboration at Mt. Chacaltaya (540 g/cm^2). Also shown is the calculation [19] based on Eq. (1), represented by the dashed line. We observe that the data in Figs. 1 and 2 are described quite well, adopting the model with violation of Feynman scaling and proton primary composition at the top of the atmosphere (Model 1). Other data are also described within the same frame of assumptions of this model, such as the vertical differential spectrum of muons [17], detected at sea level (1030 g/cm^2), and the integral energy spectrum of hadrons for the family P3'-C1-B90 [19], detected at Mt. Pamir (596 g/cm^2).

Model 2:

Approximate Feynman Scaling with Heavy Primary.

Guided by the features of QCD-inspired models (approximate Feynman scaling in the fragmentation region and an inelasticity slowly varying with energy) and obeying the behavior of air showers at ultra-high energies, Costa, Halzen and Salles [20] proposed a phenomenological model, parametrized by

$$\frac{dN}{dy} = x\frac{dN}{dx} = a\frac{(1-x)^n}{x} , \qquad (2)$$

with $a = 0.12$ and $n = 2.6$. From this model, the average inelasticity $\langle K\rangle$ is independent of energy over a broad range, and its value is in agreement with QCD-based models [22].

The attempt to describe the energy spectrum of hadronic cascades measured by Mt. Fuji, based on Eq. (2) and assuming the primary spectrum at the top of the atmosphere with $\langle A\rangle = 1$, is not successful. Instead, the correct adjustment [23] requires the primary composition to have an average mass number of $\langle A\rangle = 7.3\pm0.9$. The result is represented by the solid line in Fig. 1. It is noticeable that this value of $\langle A\rangle$ is consistent with the results obtained from underground multimuon measurements, carried out by the MACRO Collaboration [11] and the Soudan experiment [12]. Particles propagated down the atmosphere through Eq. (2) can describe very well the family-event Ursa Maior [23], as seen from the solid curve in Fig. 2. This model can also be applied to reproduce other sets of air shower data, such as the hadronic and electromagnetic energy spectra detected at Mt. Kanbala (atmospheric depth 520 g/cm^2), and the electromagnetic components at both Mt. Fuji and at Mt. Chacaltaya [23]. Similarly, good description is achieved calculating the integral spectra, as well as the energy-weighted lateral spread, for Centauro VII (Mt. Chacaltaya), and for the Pamirs family event P3'-C5-505 [20]. We therefore conclude that a fairly possible scenario for interpreting cosmic-ray data is given by the model with approximate Feynman scaling and heavy primary composition (Model 2).

IV. DISCUSSION

Summarizing, we note that there are well established air shower and family events which have been measured with reasonable accuracy, representing a solid ground for the investigation of very high energy physics, in the fragmentation region. However, there is a strong limitation on the range of information to be drawn from these data, as illustrated above by the two examples (Figs. 1 and 2). It is important to stress that the calculations were carried out within the same theoretical formalism, differing basically just on the multiparticle production model and the primary composition. Therefore, as to tell from the knowledge available at the moment, we have no clue whether deciding in favor of Model 1 or 2. This is the essence of the KAU-problem. *In fact, our conclusion goes far beyond the particular choice of the model, either 1 or 2, presented here.* Very much similar reasoning has been envisaged at different circumstances in the past. For example, M. Shibata [24] addressed to the heart of the ambiguity, through extensive Monte Carlo simulations, adopting diverse production models and chemical dominance for the calculation of gamma families measured at mountain altitudes. Both Wlodarcyk [25] and Ohsawa [15,26] investigated different models of hadronic interactions, taking average inelasticities either decreasing, constant or increasing with energy. Analyzing the hadronic and the electromagnetic components of cosmic-ray measurements, they presented results which accommodates the option for the model with decreasing inelasticity and primary proton spectrum. On the other hand, Yodh and collaborators [27] analyzed the spectra of hadrons and muons in the atmosphere, and their detailed shower simulation pointed toward no violation of scaling in the fragmentation region, provided the composition was heavy dominant. Gaisser *et al.* [28] analized the shower size maximum of Fly's Eye data, and argued that instead of decreasing inelasticity, only models with some increase on K could describe the data, also supporting the heavy primary composition hypothesis. There have been some global efforts to account for the explanation of emulsion chamber experimental results, as in the thorough study by the Chacaltaya and Pamir Collaborations [29]. The authors examined several scenarios of particle production, ranging from Feynman scaling or quasi-scaling, to strong scaling violation, and considered either the normal composition of primary particles or the heavy dominant model. Although some characteristics favored certain models, they finally ended up claiming that none of those models, based on extrapolations of accelerator results up to cosmic-ray energies, was really satisfactory and that a consistent solution should be searched outside that framework. Recently, Kawasumi *et al.* (SYS Collaboration) [30] compared air shower and family observations to conclude also that the nuclear interactions should change their feautres for energies above 10^{16} eV, in order to accomodate the data, independent of the assumption on the primary composition as proton or heavy dominant. The list of models for calculating the average inelasticity at the high energy domain mentioned here is far from complete. A summary of the "K-Models" is given in Table I. There have been also some rather extensive efforts to measure and simulate the primary all particle spectra at the top of the atmosphere [50]. Among the main progress toward the empirical determination of the primary spectrum and composition above the "knee", we highlight the Fly's Eye experiment at Utah [51], (being upgraded to the "High Resolution Eye") and, more recently, the KASCADE large experiment at Karlsruhe [52]. Ultimately, the highest energy cosmic rays (above 10^{19} eV) are to be measured by the Pierre Auger Observatory [53]. Even though, one of the conclusions inferred from Wdowczyk [54], in his detailed attempt to organize the different theoretical and experimental trends, is that whenever the results are based on simulations or calculations, they are subjected to the uncertainties arising from our incomplete knowledge of the high-energy interactions in the fragmentation region. This has also been the subject of debate at international cosmic-ray conferences and symposiums [55].

Given the state of the polemics, it is to be noted that the underlying physical basis of the KAU ambiguity is fairly understandable. A primary proton with a given energy E_o requires a "low" inelasticity in order to reproduce the energy spectra with the correct steepness. This means that the correct depletion rate of secondary particles, with relatively high energy, is only achieved if the leading particle "refuses" to deliver its energy, otherwise the flux at the high end of the spectrum would be overestimated. On the other hand, a heavy primary particle soon enough breaks into several lighter fragments, each carrying only a fraction of the initial energy E_o. As a result there is less available energy per nucleon, which requires the inelasticity to be "high" enough to feed the cascade and produce the desired multiplicity of secondaries with "low" energies, otherwise the flux at the low end of the spectrum would be underestimated.

Looking retrospectively, there seems to have no way out of this ambiguity, for both cosmic-ray and nowadays accelerator based experiments. Cosmic rays lack of the information on the primary composition at energies above the "knee" of the primary spectrum, and accelerators systematically miss the crucial detection range at the very forward (fragmentation) region. Therefore, the answer stands in the future.

Back to the times of the Superconducting Super Collider (SSC) proposal, a Full Acceptance Detector was foreseen [56]. Now, with the commissioning of the LHC at CERN, there is a new possibility opened for the construction of such a detector, by the proposition of the Forward ELastic and Inelastic eXperiment, named FELIX [57]. There are three basic features of FELIX that makes it particularly interesting to the attention and concern of the cosmic-ray community:

1. Particle production will be investigated in detail at energies up to $\sqrt{s} = 14$ TeV, corresponding in the laboratory system to $E_o \approx 10^{17}$ eV (or 10^5 TeV), well above the "knee";

2. The unique capability to measure precisely the energy and particle flow in pp collisions over the entire kinematics range, up to pseudorapidities $\eta \approx 10$, covering the region in phase space where most of the cosmic-ray information comes from;

3. Interactions will be carried out on either proton-proton (pp), proton-ion ($p-A$) and ion-ion ($A-A$) regimes, which brings in the essential feature of

proton-air and nucleus-air interactions in the atmosphere.

FELIX will make use of the extraordinary energies and luminosities produced by the LHC beam and may cover a list of topics not dealt by any other of the experimental programs currently approved by, or proposed to, the LHC Committee. The FELIX detector has a particular suitability to measure the rapidity density distribution of secondary particles, dN/dy, at exceptional high energies, and over a such extended range of rapidities. Together with its lever arm to investigate heavy ions collisions, it will clearly represent a landmark in the understanding of the dynamics of particle interactions, on a domain so closely related to those of cosmic-ray observations. It will bring in the missing piece to solve the long lasting KAU-problem, deciding between Model 1 or Model 2, or anything else. In that way, the accelerator based experiment will be giving the key to unveil the intriguing questions concerning the composition and origin of the highest energy primary cosmic rays. And, that is not the whole story. In the previous discussion of emulsion chamber events, we avoided on purpose to consider some of the exotic events, such as Centauro I. The reason is that the attempts to describe such observations failed for any of the models presented here, or any similar ones. However, there are evidences [58] that the Disoriented Chiral Condensate effect [59], to be searched for by FELIX, could be the explanation of these - and other - anomalies, still intriguing the cosmic-ray community.

ACKNOWLEDGMENTS

The author is thankful to Francis Halzen for so many discussions and suggestions. Thanks also to Dan Marques for pointing out that "Kau" means "the vital fluid" in the native South-american language Tupi-Guarani. This research was supported in part by the U.S. Department of Energy under Grant No. DE-FG02-95ER40896, and by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation.

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TABLE I. Particle production and inelasticity models (K-Models).

Author(s)	Remarks	Data Described	
		Type[a]	Experiment[b]
Decreasing Inelasticity			
Ohsawa and Sawayanagi [15]	Eq. (1) / Model 1	ES	[17] Fuji/Sea Level [19] Chacaltaya/Pamir
Fowler *et al.* [31]	Interacting Gluon Model	ID	CERN ISR
He [32]	pp/e^+e^- similarities	CM	Accelerator
Kadija and Martins [33]	pp/e^+e^- similarities	ID, CM	Accelerator
Kawasumi *et al.* [30]	Proton or heavy	ES, SS	Chacaltaya/Tien Shan
Kempa *et al.* [34]	Proton dominance	ES	Fuji/JACEE
Linkai and Qingqi [35]	2-component Model	dN/dy	UA5, UA7
Wdowczyc and Wolfendale [36]	Scale-Breaking Model	ES, $dN/d\eta$	Fuji/Accelerator
Wlodarcyk [25]	Valon-Gluon Model	AL,ES,SM	Pamir/Akeno
Constant or Slowly Increasing Inelasticity			
Costa, Halzen and Salles [20,23]	Eq. (2) / Model 2	ES, LS	Fuji/Kanbala Chacaltaya/Pamir
Dunaevsky [37]	Quark-Gluon Strings	CM,ES,LS	Pamir/Tien Shan
Durães *et al.* [38]	Interacting-Gluon/Mini-Jet	ID	Accelerator
Gaisser and Stanev [28,39]	Mini-Jet Model	SM, $dN/d\eta$	Fly's Eye/Accelerator
Mikhamedshin [40]	Heavy primary	ES, LS	Pamir
Norikura Group [41]	Heavy primary	ES	Mt. Norikura
Ren *et al.* [42]	Heavy primary	ES	Fuji/Kanbala
Increasing Inelasticity			
Barshay and Chiba [43]	Eikonal Blackening	CM	Accelerator
Capdevielle [44]	Dual Parton Model	SM, $dN/d\eta$	Mountain/Accelerator
Dias de Deus [45]	Geometrical Model	ES, $d\sigma/dx$	Mountain/Accelerator
Kaidalov *et al.* [46]	Quark-Gluon Strings	CM	Accelerator
KNP [21]	QCD-Pomeron	$\sigma_{total}^{pp(p\bar{p})}$	CERN S$p\bar{p}$S
Shabelski *et al.* [47]	Additive Quark Model	CM	Accelerator
Combination of Models			
Baradzei *et al.* [29]	Proton/Fe dominance	ES, LS	Chacaltaya/Pamir
Capdevielle *et al.* [48]	Proton/Heavy dominance	ES, SS	Pamir/Tien Shan
Kasahara *et al.* [49]	Proton/Fe dominance	ES, LS	Fuji
Shibata [24]	Several K-A parameters	γ-families	Fuji

[a]AL= Attenuattion Lenght; CM= Charged Multiplicity; ES= Energy Spectra;
ID= Inelasticity Distribution; LS= Lateral Spread; SM= Shower Maximum; SS = Shower Size.
[b]Terms *Accelerator* and *Mountain* refer to miscelaneous experiments and data sources.

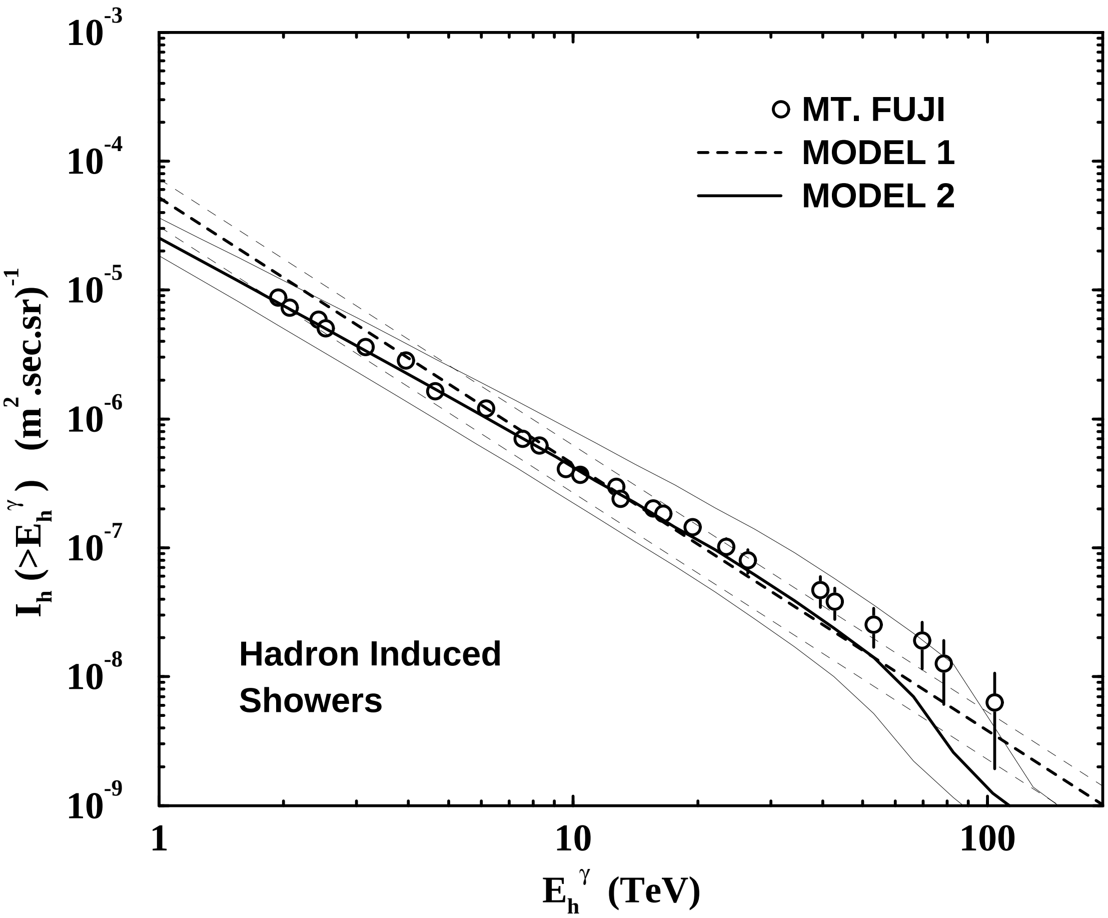

FIG. 1. Energy spectrum of hadronic showers detected at Mt. Fuji [16]. Experimental data (◯) are compared to the calculations with Model 1 (scaling violation and proton primary, dashed line) and Model 2 (Feynman scaling and heavy primary, solid line). Fine dashed and solid lines are calculated from uncertainities in the primary spectrum slope and composition.

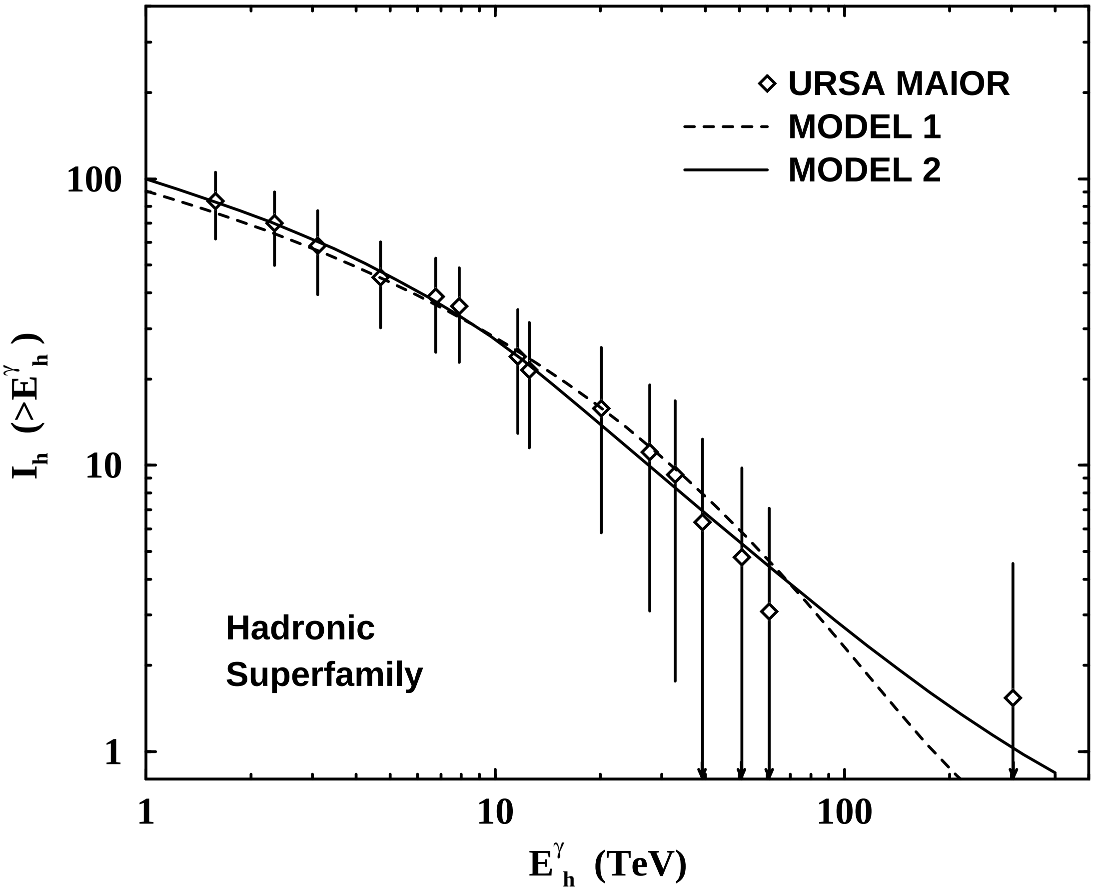

FIG. 2. Hadronic Integral energy spectra of the superfamily event Ursa Maior, detected at Mt. Chacaltaya [18]. Experimental data (◇) are compared to the calculations with Model 1 (dashed line) and Model 2 (solid line).