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Accelerator measurements needed to resolve uncertainties in primary cosmic ray composition and inelasticity

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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 measurements of particle production at and near zero degrees—at extreme values of rapidity (or pseudorapidity)—can overcome these uncertainties. Experiments of this nature are possible at the Fermilab Tevatron and will be possible at the CERN Large Hadron Collider, and should resolve the questions concerning the interpretation of cosmic ray data up to the highest measured energies. [S0556-2821(98)04507-X]

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I. INTRODUCTION

Since the identification of cosmic rays by Viktor Hess, during his balloon flights in 1911–1912, 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 (1949–1951), and sigma and cascade particles (1952–1953). Then came the accelerator era. Previous cosmic-ray discoveries were confirmed in laboratories. Moreover, accelerators produced beams with energies comparable to those available from cosmic rays, with the advantages of high intensity as well as precise knowledge of the beam energy and direction. For that reason, the interest in cosmic rays moved to problems on their origin and their propagation through the interstellar medium. Nevertheless, over the past decades, cosmic-ray physics has accumulated some surprising observations, 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—do not always come together.

In the discussion to follow, we attempt to address the status of those requirements, considering a specific case in the range 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 indicate how accelerator measurements of particle production at and near zero degrees can overcome present uncertainties and help answer some of the outstanding puzzles in cosmic-ray physics.

II. COSMIC-RAY ANOMALIES

Some unexpected results have been found in recent cosmic-ray experiments [3]: 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. These anomalies have been measured, confirmed, and remain unexplained. 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 share one feature: there has not been an agreed-upon explanation for any of them over the past 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 indicate 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 constraint 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: (a) the dynamics of multiparticle production, which dictates the behavior of the inelasticity K, i.e., the fraction of the collision energy going into the production of secondaries, and (b) 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. KAU PROBLEM

To better appreciate the extension of the KAU problem, we consider, as an example, two sample models of particle production, investigating the constraints 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]

$$\frac{dN}{dy}=x\frac{dN}{dx}=\frac{5}{3}\left(\frac{s}{s_0}\right)^{\alpha}\left[1-\left(\frac{s}{s_0'}\right)^{\alpha'}x\right]^4, \qquad (1)$$

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 $\alpha=0.11$, $\alpha'=0.17$, $s_0=6.3\times10^2$ GeV^2 and $s_0'=1.8\times10^3$ 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.

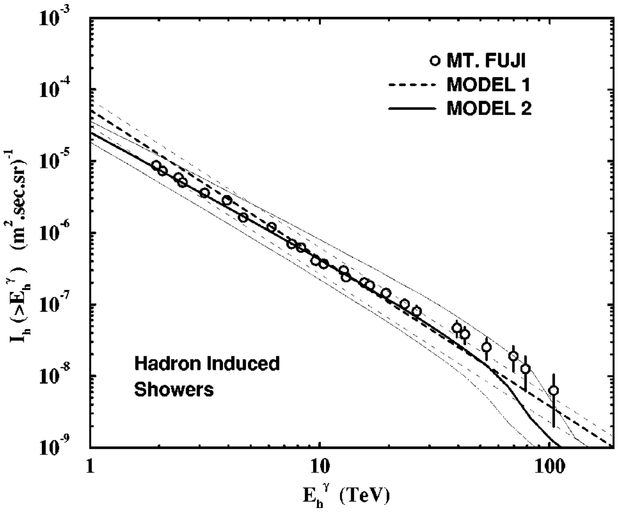

FIG. 1. Energy spectrum of hadronic showers detected at Mt. Fuji [16]. Experimental data (○) are compared to the calculations with model 1 (scaling violation and proton primary, dashed line) and model 2 (Feynman scaling and heavy primary, solid line). Fine dashed and solid lines are calculated from uncertainities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

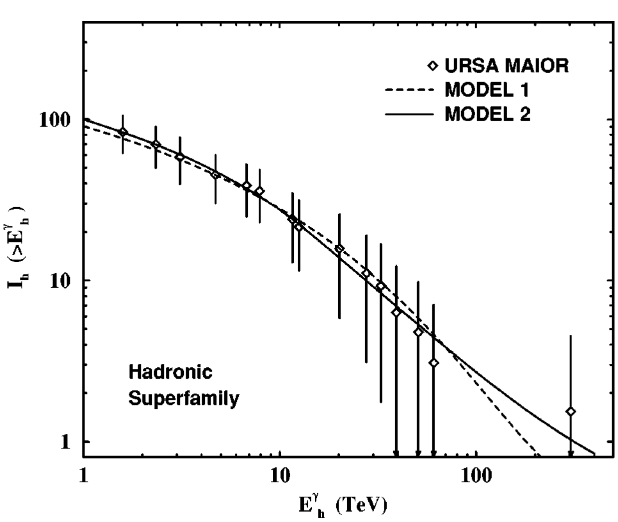

FIG. 2. Hadronic integral energy spectra of the superfamily event Ursa Maior, detected at Mt. Chacaltaya [18]. Experimental data (◇) are compared to the calculations with model 1 (dashed line) and model 2 (solid line).

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. At this point we remark that no one truly believes that primary cosmic rays below 10^{19} eV are *all* protons; the issue is rather whether the mass (atomic number) distribution becomes heavier or lighter than observed directly at energies below 10^{14} eV. Nevertheless, it is still relevant that some observations can be fit with $\langle A\rangle$ of 1 and an appropriate choice of $\langle K\rangle$. This calculation is therefore to be regarded as an extreme example of the KAU problem. Consider, for this purpose, 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.'' Figure 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

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

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 [21].

The attempt to describe the energy spectrum of hadronic cascades measured by Mt. Fuji, based on Eq. (2) and assuming a proton primary spectrum at the top of the atmosphere, is not successful. Instead, the correct adjustment [22] requires the primary composition to have an average mass number of $\langle A\rangle=7.3\pm0.9$ (or $\langle \ln A\rangle=2.0\pm0.1$). 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) describe very well the family-event Ursa Maior [22], 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 [22]. Similarly, good agreement is achieved between the data and the calculated integral spectra as well as the energy-weighted lateral spread of the event 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.

The hypothesis that all high energy cosmic rays are protons and that particle production obeys Feynman scaling cannot accommodate the data. In such a model, energy is not dissipated fast enough to match the observations. For achieving faster dissipation in the atmosphere we need either to consider an abundant particle production by violation of Feynman scaling (as in model 1) or to subdivide the energy between nucleons of heavy nuclear primaries (as in model 2). Here lies the source of the ambiguity, and from the knowledge available at the moment, we have no clue for 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 similar reasoning has been envisaged on different occasions in the past. For example, Shibata [23] addressed 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 [24] and Ohsawa and Sawayanagi [15,25] 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 accommodate the option for the model with decreasing inelasticity and primary proton spectrum. On the other hand, Yodh and collaborators [26] 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.* [27] analyzed 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 serious efforts to understand the emulsion chamber experimental results, as in the thorough study by the Chacaltaya and Pamir Collaborations [28]. 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 for outside that framework. Recently, Kawasumi *et al.* (SYS Collaboration) [29] compared air shower and family observations to conclude also that the nuclear interactions should change their features for energies above 10^{16} eV, in order to accommodate 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 [51]. Among the main advances toward the empirical determination of the primary spectrum and composition above the ''knee,'' we highlight the Fly's Eye experiment at Utah [52], being upgraded to the ''High Resolution Eye.'' More recently, through the combination of various advanced

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

		Data described	
Author(s)	Remarks	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.* [30]	Interacting gluon model	ID	CERN ISR
He [31]	pp/e^+e^- similarities	CM	Accelerator
Kadija and Martins [32]	pp/e^+e^- similarities	ID, CM	Accelerator
Kawasumi *et al.* [29]	Proton or heavy	ES, SS	Chacaltaya/Tien Shan
Kempa *et al.* [33]	Proton dominance	ES	Fuji/JACEE
Ding and Zhu [34]	Two-component model	dN/dy	UA5, UA7
Wdowczyk and Wolfendale [35]	Scale-breaking model	ES, $dN/d\eta$	Fuji/Accelerator
Wlodarcyk [24]	Valon-gluon model	AL,ES,SM	Pamir/Akeno
Constant or slowly increasing inelasticity			
Costa, Halzen and Salles [20,22]	Eq. (2)/model 2	ES, LS	Fuji/Kanbala Chacaltaya/Pamir
Dunaevsky [36]	Quark-gluon strings	CM, ES, LS	Pamir/Tien Shan
Durães *et al.* [37]	Interacting-gluon/mini-jet	ID	Accelerator
Gaisser and Stanev [27,38]	Mini-jet model	SM, $dN/d\eta$	Fly's Eye/Accelerator
Mukhamedshin [39]	Heavy primary	ES, LS	Pamir
Norikura Group [40]	Heavy primary	ES	Mt. Norikura
Ren *et al.* [41]	Heavy primary	ES	Fuji/Kanbala
Increasing inelasticity			
Barshay and Chiba [42]	Eikonal blackening	CM	Accelerator
Capdevielle [43]	Dual parton model	SM, $dN/d\eta$	Mountain/Accelerator
Dias de Deus [44]	Geometrical model	ES, $d\sigma/dx$	Mountain/Accelerator
Kaidalov *et al.* [45]	Quark-gluon strings	CM	Accelerator
KNP [46]	QCD-Pomeron	$\sigma_{total}^{pp(p\bar{p})}$	CERN $Sp\bar{p}S$
Shabelski *et al.* [47]	Additive quark model	CM	Accelerator
Combination of models			
Baradzei *et al.* [28]	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
Klages *et al.* [50]	Several parameters	ES, LS, SS	KASCADE
Shibata [23]	Several K-A parameters	γ-families	Fuji

[a] AL=attenuation length, 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 miscellaneous experiments and data sources.

detection techniques for the electromagnetic, the muonic, and the hadronic component of extensive air showers, the KASCADE project [50], led by the Karlsruhe group, made and reported extensive analyses in connection with the determination of the chemical composition in the energy range around and above the ''knee'' of the primary spectrum. The strength of the experiment lies in the large number of experimental quantities which can be measured simultaneously for each individual event, enabling multidimensional analyses for the determination of its basic properties (mass and energy of the primary). Ultimately, the highest energy cosmic rays (above 10^{19} eV) are to be measured by the Pierre Auger Observatory [53]. Even so, 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 symposia [55].

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

There is a new generation of accelerator based experiments under consideration that could—and should—be used as appropriate tools to investigate cosmic-ray related phenomena. Some are inspired by the Full Acceptance Detector foreseen at the time of the Superconducting Super Collider (SSC) proposal [56]. Actually, there is no need to wait for accelerator energies to achieve the SSC range. Experiments relevant to cosmic-ray observations are possible at the Fermilab Tevatron ($\sqrt{s}=1.8$ TeV, corresponding to a laboratory energy $E_0=1.7\times10^{15}$ eV for a proton on a stationary nucleon) and will be possible at the CERN Large Hadron Collider (LHC, with $\sqrt{s}=14$ TeV, $E_0=10^{17}$ eV). The corresponding rapidity ranges are from 0 up to 15.2 and to 19.2, respectively.

As summarized by Jones [57], some recent results from Fermilab Tevatron experiments related to forward particle production are of particular interest. For example, we have the data analysis from Minimax, the investigation of rapidity gaps by the D0 Collaboration and the studies of diffractive W production by the Collider Detector at Fermilab (CDF) Collaboration. There are also groups suggesting new experiments for the Tevatron. A Zero Degree Detector would measure the spectrum of neutral and charged particles at very forward angles from the Collider, in the C0 area. The physics agenda would cover the production of photons (including the determination of π^0 and η^0 spectra), neutrons and antineutrons, Λ^0 and $\overline{\Lambda^0}$, and total charged particles, from zero degrees to angles of several mrad at all energies, up to $\sqrt{s}\approx2$ TeV. The possibility of adding particle identification would allow charged pions, kaons, and protons to be distinguished. A Forward Proton Detector would make use of calorimetry, tracking and high luminosities available at the D0 detector to facilitate studies of the structure of the pomeron (including its dependence on diffractive mass and momentum transfer), the determination of the quark gluon content of the pomeron, the search for diffractive production of heavy objects such as W bosons, and the studies of hard double Pomeron exchange. A full investigation of hard diffraction and of double Pomeron events by means of such a detector would improve the studies of the nature of Pomerons carried out by rapidity gap techniques. Furthermore, it is believed that cosmic-ray exotic events, such as Centauros, may be related to diffractive phenomena [58].

The commissioning of the CERN Large Hadron Collider (LHC) opens new possibilities to explore. There is the proposition of a forward elastic and inelastic experiment, named FELIX [59]. This full acceptance detector would be able to measure almost completely the energy and the particle flow in pp collisions over the entire kinematics range, down to zero degree production angle. Such an experiment would be aimed at the detailed investigation of strong interactions, diffractive processes, electroweak rapidity gaps, elastic scattering and, of particular interest, it would pursue the precise measurement of forward particle production at the LHC energy range, which goes well above the cosmic-ray ‘‘knee.’’ In addition, interactions are to be produced on either proton-proton (pp), proton-ion (p-A) and ion-ion (A-A) regimes, and will elucidate the essential feature of proton-air and nucleus-air interactions in the atmosphere. Altogether, the detector would have a special suitability to measure the rapidity density distribution of secondary particles, dN/dy, covering the region in phase space from which most of the cosmic-ray information comes from.

Accelerator experiments as mentioned above 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, accelerator based measurements will give the key to unveil intriguing questions concerning the composition and origin of the highest energy primary cosmic rays. As a final remark, we note that, in the previous discussion of emulsion chamber events, we avoided on purpose the consideration of some of the exotic events, such as Centauro I. The reason is that attempts to describe such observations failed for the models presented here, or any similar ones. There are indications [60] that the disoriented chiral ccondensate effect [61], to be searched for by the new generation of accelerator detectors, could be the explanation of these—and other—anomalies still intriguing the cosmic-ray community.

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[1] C. M. G. Lattes, Y. Fujimoto and S. Hasegawa, Phys. Rep. **65**, 151 (1980).
[2] S. Hasegawa and M. Tamada, Nucl. Phys. **B474**, 141 (1996).
[3] For a recent compilation see F. Halzen and L. W. Jones, ‘‘FELIX: The Astroparticle Connection,’’ University of Wisconsin–Madison Report No. MADPH-97-998 (1997), and references therein [incorporated in E. Lippmaa *et al.*, ‘‘FELIX, a Full Acceptance Detector at the LHC–Letter of Intent,’’ CERN-LHCC-97-45 (1997), Chap. 2, Sec. 5, p. 70].
[4] M. S. Longair, *High Energy Astrophysics* (Cambridge University Press, Cambridge, England, 1992), Chap. 9.
[5] T. Stanev *et al.*, Phys. Rev. Lett. **75**, 3056 (1995).
[6] T. Stanev and H. P. Vankov, Phys. Rev. D **55**, 1365 (1997).
[7] F. Halzen, summary talk to appear in the Proceedings of the 32nd Rencontre de Moriond, ‘‘Very High Energy Phenomena in the Universe,’’ Les Arcs, France, 1997, edited by Y. Giraud-Heraud and J. Tran Thanh Van (Editions Frontieres, Paris, 1997), p. 229; to appear in the Proceedings of the International Workshop ‘‘New Worlds in Astroparticle Physics,’’ Faro, Portugal, 1996 (unpublished).
[8] A. M. Hillas, Annu. Rev. Astron. Astrophys. **22**, 425 (1984); see also A. A. Watson, in Proceedings of the 19th International Cosmic Ray Conference, La Jolla, 1985, Vol. 9, p. 111.
[9] See, for example, The JACEE Collaboration, T. H. Burnett

et al., Nucl. Instrum. Methods Phys. Res. A **251**, 583 (1986).

[10] T. K. Gaisser, *Cosmic Rays and Particle Physics* (Cambridge University Press, Cambridge, 1992).

[11] MACRO Collaboration, in *Proceedings of the 24th International Cosmic Ray Conference*, Rome, Italy, 1995, edited by B. D'Ettorre Piazzoli *et al.* (Arti Grafiche Editoriali, Urbino, 1995), Vol. 2, p. 689.

[12] S. M. Kasahara *et al.*, Phys. Rev. D **55**, 5282 (1997).

[13] UA5 Collaboration, G. T. Alner *et al.*, Z. Phys. C **33**, 1 (1986).

[14] E. Pare *et al.*, Phys. Lett. B **242**, 531 (1990).

[15] A. Ohsawa and K. Sawayanagi, Phys. Rev. D **45**, 3128 (1992).

[16] Mt. Fuji Collaboration, M. Akashi *et al.*, Nuovo Cimento A **65**, 355 (1981).

[17] J. Bellandi *et al.*, Nuovo Cimento **A 107**, 1339 (1994).

[18] J. A. Chinellato, Ph.D thesis, Universidade Estadual de Campinas, Brazil, 1981.

[19] J. Bellandi *et al.*, Phys. Rev. D **50**, 6836 (1994).

[20] C. G. S. Costa, F. Halzen, and C. Salles, Phys. Rev. D **52**, 3890 (1995).

[21] See, for example, T. K. Gaisser *et al.*, in *Proceedings of the 21th International Cosmic Ray Conference*, Adelaide, Australia, edited by R. J. Protheroe (Graphic Services, Northfield, 1990), Vol. 8, p. 55; L. Durand and H. Pi, in *Elastic and Diffractive Scatterings*, Proceedings of the Conference, Evanston, Illinois, 1989, edited by M. Block and A. White [Nucl. Phys. B (Proc. Suppl.) **12**, 379 (1990)].

[22] C. G. S. Costa *et al.*, Phys. Rev. D **54**, 5558 (1996).

[23] M. Shibata, Phys. Rev. D **24**, 1847 (1981).

[24] Z. Wlodarczyk, J. Phys. G **19**, L133 (1993); **21**, 281 (1995); see also R. M. Weiner *et al.*, Phys. Rev. D **45**, 2308 (1992); Yu. A. Shabelski *et al.*, J. Phys. G **18**, 1281 (1992).

[25] A. Ohsawa, Prog. Theor. Phys. **92**, 1005 (1994).

[26] G. B. Yodh *et al.*, Nucl. Phys. **B183**, 12 (1981), Phys. Rev. D **23**, 764 (1981).

[27] T. K. Gaisser *et al.*, Phys. Rev. D **47**, 1919 (1993).

[28] Chacaltaya and Pamir Collaborations, L. T. Baradzei *et al.*, Nucl. Phys. **B370**, 365 (1992).

[29] N. Kawasumi *et al.*, Phys. Rev. D **53**, 3534 (1996).

[30] G. N. Fowler *et al.*, Phys. Lett. **145B**, 407 (1984); Phys. Rev. Lett. **55**, 173 (1985); Phys. Rev. D **35**, 870 (1987); Phys. Rev. C **40**, 1219 (1989).

[31] Y. D. He, J. Phys. G **19**, 1953 (1993).

[32] K. Kadija and M. Martinis, Phys. Rev. D **48**, 2027 (1993).

[33] J. Kempa and J. Wdowczyk, J. Phys. G **9**, 127 (1983).

[34] L. K. Ding and Q. Q. Zhu, Phys. Lett. B **297**, 201 (1992).

[35] J. Wdowczyk and A. W. Wolfendale, J. Phys. G **10**, 257 (1984); **13**, 411 (1987).

[36] A. M. Dunaevsky, in Proceedings of the 22nd International Cosmic Ray Conference, Dublin, Ireland, 1991, Vol. 4, p. 133 and p. 161; Pamir Collaboration, A. S. Borisov *et al.*, *ibid.*, Vol. 4, p. 119.

[37] F. O. Durães, F. S. Navarra, and G. Wilk, Phys. Rev. D **47**, 3049 (1993).

[38] T. K. Gaisser and T. Stanev, Phys. Lett. B **219**, 375 (1989).

[39] R. A. Mukhamedshin, in Proceedings of the 17th International Cosmic Ray Conference, Paris, France, 1981, Vol. 5, p. 343 and p. 347; V. A. Astafiev and R. A. Mukhamedshin, in Proceedings of the 16th International Cosmic Ray Conference, Kyoto, Japan, 1979, Vol. 7, p. 204.

[40] Y. Fukushima *et al.*, Phys. Rev. D **39**, 1267 (1989); M. Shima *et al.*, *ibid.* **39**, 1275 (1989); To. Saito *et al.*, Astropart. Phys. **1**, 257 (1993).

[41] J. R. Ren *et al.*, Phys. Rev. D **38**, 1404 (1988).

[42] S. Barshay and Y. Chiba, Phys. Lett. **167B**, 449 (1986).

[43] J. N. Capdevielle, J. Phys. G **15**, 909 (1989).

[44] J. Dias de Deus, Phys. Rev. D **32**, 2334 (1985); see also J. Bellandi, J. Dias de Deus *et al.*, Nuovo Cimento **A 101**, 897 (1989); J. Phys. G **18**, 579 (1992).

[45] A. Kaidalov and Ter. Martyrosian, Phys. Lett. **117B**, 247 (1982).

[46] B. Z. Kopeliovich, N. N. Nikolaev, and I. K. Potashnikova, Phys. Rev. D **39**, 769 (1989); N. N. Nikolaev, *ibid.* **48**, R1904 (1993).

[47] Yu. A. Shabelski, Z. Phys. C **38**, 569 (1988); V. V. Anisovich *et al.*, *ibid.* **27**, 77 (1985).

[48] J. N. Capdevielle *et al.*, J. Phys. G **20**, 947 (1994).

[49] K. Kasahara *et al.*, Prog. Theor. Phys. **6**, 55 (1976); in Proceedings of the 16th International Cosmic Ray Conference [39], Vol. 13, p. 70 and p. 76.

[50] KASCADE Collaboration, H. O. Klanges *et al.*, in *Very High Energy Cosmic Ray Interactions*, Proceedings of the International Symposium, Karlsruhe, Germany, 1996, edited by H. Rebel *et al.* [Nucl. Phys. B (Proc. Suppl.) **52**, 92 (1997)].

[51] T. Shibata, in *Proceedings of the 24th International Cosmic Ray Conference*, Rome, Italy, 1995, edited by N. Iucci and E. Lamanna (Editrice Compositori, Bologna, 1997), Invited, Rapporteurs and Highlight Papers, p. 713.

[52] D. J. Bird *et al.*, Phys. Rev. Lett. **71**, 3401 (1993).

[53] C. Hojvat, to appear in the Proceedings of the 32nd Rencontre de Moriond, ''Very High Energy Phenomena in the Universe'' [7].

[54] J. Wdowczyk, J. Phys. G **20**, 1001 (1994).

[55] See, for example, T. Yuda, in Proceedings of the 22nd International Cosmic Ray Conference, Dublin, Ireland, 1991, Vol. 5, p. 313; F. Halzen, in *VIIth International Symposium on Very High Energy Cosmic Ray Interactions*, edited by L. Jones, AIP Conf. Proc. No. 276 (AIP, New York, 1993), p. 679.

[56] J. D. Bjorken, Int. J. Mod. Phys. A **7**, 4189 (1992); in *VIIth International Symposium on Very High Energy Cosmic Ray Interactions* [55], p. 667.

[57] L. W. Jones, in *Very High Energy Cosmic Ray Interactions* [50], p. 103.

[58] K. Goulianos, in *VIIth International Symposium on Very High Energy Cosmic Ray Interactions* [55], p. 244; C. E. Navia *et al.*, Phys. Rev. D **50**, 5732 (1994).

[59] K. Eggert and C. Taylor, in *Very High Energy Cosmic Rray Interactions* [50], p. 279.

[60] C. E. Navia *et al.*, Phys. Rev. D **55**, 5834 (1997).

[61] T. C. Brooks *et al.*, Phys. Rev. D **55**, 5667 (1997).