Cosmic Ray Astrophysics and Hadronic Interactions
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Research in cosmic rays is now nearly a century old, but most of the fundamental questions in this field remain unanswered, on the other hand the perspectives of future studies in the next decade are very bright. New detectors will provide higher quality data in the entire energy range from $10^8$ to $10^{20}$ eV (or more if particles of higher energy have non negligible fluxes), moreover cosmic ray astrophysics must now be considered, together with gamma, neutrino and gravitational wave astronomy, as one of the subfields of high energy astrophysics, and using information from these four “messengers” there is the potential of a detailed understanding of the origin of the high energy radiation in the universe. High energy cosmic rays are measured indirectly observing the showers they generate in the atmosphere, and a correct and detailed interpretation of these measurements will require an improved understanding of the properties of hadronic interactions. The new collider experiments, and in particular the LHC project at CERN offer the unique possibility to perform measurements of great value for cosmic ray astrophysics. It is of great importance for cosmic research that this possibility is fully exploited with the appropriate instrumentation and analysis.

1. High Energy Astrophysics and Fundamental Science

Progress in fundamental science requires the study of “extreme physical systems”, where the deeper structure of the physical laws can become visible, such “extreme systems” can be constructed in the laboratory, or can be found in nature. Particle accelerators can be seen as instruments for the construction of extreme systems (composed of few very high energy particles) to study the properties of interactions at very small distances. The history of astrophysics can also be seen as the discovery and the study of more and more “exotic” objects (or events): normal stars, white dwarfs, neutron stars, supernova explosions, Active Galactic Nuclei, Gamma Ray Bursts, . . ., whose understanding requires a deeper and more refined description of the physical laws. Cosmology allows the study of the early universe, and going back in time explores progressively more and more extreme conditions, in fact of “arbitrary extremeness”, and constitutes the ultimate laboratory for fundamental science. The three fields of Particle Physics, Astrophysics and Cosmology appear today as more and more strictly interconnected fields.

The research on Cosmic Rays is a crucial element in High Energy Astrophysics, and has a particular deep relation with Particle Physics. This relation is historical and methodological. The two fields started essentially at the same time, at the beginning of the last century, and the measurement of the fluxes of cosmic rays clearly required, and at the same time made possible an understanding of the interaction properties of high energy elementary particles. Research in cosmic rays in the years between 1930 and 1960 resulted in the discovery of the first elementary particles (after the electron): the positron $e^+$, the second charged lepton $\mu^\pm$, the charged and neutral pions $\pi^\pm$, $\pi^0$, the strange particles $\Lambda$, $K^\pm$, $K_L$, $K_S$ (the $\theta - \tau$ puzzle). Also the discovery of the anti-proton in 1955 happened essentially simultaneously at the Berkeley Bevatron, and in emulsions exposed to cosmic rays. Then, in the 1950’s, particle physics entered in the era of big machines and big detectors. An extraordinary experimental and intellectual effort culminated in the construction of the “Standard Model”, based on the gauge group $SU(3) \otimes SU(2) \otimes U(1)$, with great predictive power and a set of open questions that have inspired new and very complex experimental projects such as LHC. During the “accelerator era” the direction of scientific input flowed mostly
in the other direction, from particle physics to cosmic ray research. Experiments at the ISR, the SpS and the Tevatron colliders measured the interaction properties of high energy protons, allowing a more accurate interpretation of the showers produced high energy cosmic rays.

Progress in cosmic ray research has been slow and after nearly a century of intense efforts, it is fair to say that the most important questions in the field remain without (unambiguous) answers. The near future of cosmic ray research appears however as extraordinarily interesting, and it seems likely that in the next decade we will see dramatic advances in our understanding of the high energy radiation. A main reason for this expectation is that cosmic ray research has matured into one component of high energy astrophysics, together with $\gamma$–astronomy $^2$, that in the last decade has produced a set of remarkable results, and $\nu$–astronomy $^3$ that, after the observations of the sun and SN1987a, is now aiming at the detection of high energy sources using new large volume $\nu$–telescopes. Hopefully gravitational waves will also be soon observed and we will receive four different “messengers” ($\gamma, \nu, \text{c.r.}$ and g.w.) from astrophysical objects. With the combined efforts of these four fields, the identification and detailed understanding of sources of galactic and extra–galactic cosmic rays appears possible after nearly a century of efforts.

Cosmic ray measurements are also giving (controversial) indications of the existence of unexpected phenomena. The most interesting results is the suggestion that there are significant fluxes of particles with energy as large as several times $10^{20}$ eV, in contrast with the expectation that particle of such high energy cannot propagate for long distances. If this result is confirmed by the future experiments (and we will soon know) the consequences can be extraordinarily deep.

The series of the ISVHECRI (International Symposia on Very–High Energy Cosmic Ray interaction) discuss the science at the intersection of the two fields of Particle Physics and Cosmic Ray Astrophysics. Research in cosmic rays is offering to particle physics some exciting (but again controversial) hints of “new physics” such as the existence of centauro events and of particles above the GZK cutoff; on the other hand it also has some “requests”, addressed in particular to the community of physicists working on the hadron colliders. The request is to measure at accelerators (and especially at the LHC) the main features of the very high energy hadronic collisions, in order to interpret accurately the present and future data on the highest energy hadronic showers. This is in fact a difficult and costly experimental challenge, but the motivations are strong and clear.

2. Cosmic Ray Measurements

In fig. 1 we show some measurements of the energy spectrum of cosmic rays. One can identify several energy regions:

![Figure 1. Some recent measurements of the c.r. spectra. The p and He spectra were taken in June 1998. The lines are extrapolations of fits to the direct measurements $^1$ using the ansatz $^1$ for the knee.]

$^[1]$ A lower energy region ($E \lesssim 30$ GeV) where the energy spectrum is not a simple power law but has “curvature” in a log–log plot. In this region the fluxes of c.r. have a time dependence due to modulations produced by the time varying solar wind intensity. The new measurements with magnetic...
spectrometers have reduced significantly the uncertainties of the flux below 100 GeV, and measurements taken at different times allow to study the solar modulation, extracting the interstellar flux. There is still a significant difference of

order 15–20% between quasi–simultaneous measurements performed by the BESS [4] and AMS [5] detectors (with higher flux) and CAPRICE [6] (lower flux) see fig. 2 that need to be resolved.

The main goal of the AMS detector [7] is the search for anti–nuclei in the cosmic ray fluxes. The discovery of these particle would clearly be of profound significance for both astrophysics and particle physics [8]; the detector will soon start three years of data–taking aboard the International Space Station, using a high field superconducting magnet, obtaining data of unprecedented accuracy. The detailed study of the shape of the energy fluxes of different particle species (p, nuclei, $e^\pm$, $\bar{p}$) in the this low energy region has the potential to give very valuable information about the injection, acceleration and galactic and solar environment propagation of the cosmic rays.

[iii] In the region ($3 \times 10^{11}$ eV $\leq E \leq 10^{15}$ eV) the cosmic rays fluxes to a good approximation are described by a simple power law ($\phi_A(E) \propto E^{-\alpha}$). In this region there are only few measurements mostly obtained with calorimeter on balloons, such as JACEE [9] and RUNJOB [10]. There are some indications that index $\alpha$ of the spectra of different components differ and in particular that the helium spectrum is slightly harder than $p$ one ($\alpha(p) > \alpha(\text{He})$). This is an important point and need to be confirmed by new more precise measurements. Data of an upgraded version of the BESS detector (BESS–TeV) should soon become available possibly resolving this question.

At the so called “knee” (at $E \sim 3 \times 10^{15}$ eV) the all–particle spectrum steepens, with a change in slope $\Delta \alpha \simeq 0.35$. The measurements of the spectrum in this region are only obtained with indirect measurements\(^1\). A subset of recent measurements is shown in fig. 3, where we can see that significant discrepancies exist among the different measurements. It is still a matter of debate how much of the differences is due to experimental systematic errors, and how much is due to uncertainties in the modeling of the shower development.

In fig. 1 the different lines are the extrapolation of a fit [12] of direct measurements of the cosmic ray fluxes. There is some tension between the results of such extrapolations with the highest estimates of the flux in the knee region by EAS experiments.

A significant amount of energy has gone into the determination of the mass composition of cosmic rays below and above the knee. Perhaps the simplest model for such an evolution is the assumption that the knee corresponds to a fixed value of the rigidity $p/Z e$, and therefore for the nuclear component of electric charge $Z$:

$$E_{\text{knee}}(Z) = Z E_{\text{knee}}(p).$$

Equation (1) is predicted in a very wide range of models, where the knee is the consequence of the rigidity dependence of the acceleration rate in the sources, or the galactic containment properties of cosmic rays. The ansatz (1) is used in the extrapolation of the spectra shown in fig. 1.

\(^1\)Clearly an important direction of progress is to push the direct measurements to the highest possible energy, approaching the knee. Ultra long duration (60–100 days) balloon flights in the Antartics offer this possibility. The Cream detector [11] is designed for this purpose.
Figure 3. Recent measurements of the c.r. spectrum at the knee.

There is mounting evidence \[13,14\] that the average mass of cosmic rays increases with energy across the knee, and more precisely that equation (1) is valid, however large systematic uncertainties are still existing, and are mostly due to uncertainties in the modeling of cosmic ray interactions.

In very simplified terms the determination of a mass composition is obtained with the measurement of (at least) two quantities per shower, such as the electromagnetic size \(N_e\) and the muon number \(N_\mu\). These quantities have different dependences on the energy and mass of the primary, and therefore this allows in principle to obtain estimates of \(E\) and \(A\) for each shower. For example, for the case of \(N_e\) and \(N_\mu\) qualitatively one has:

\[
N_e \simeq K_e \ A \left( \frac{E}{A} \right)^\alpha \quad \text{with } \alpha > 1 \\
N_\mu \simeq K_\mu \ A \left( \frac{E}{A} \right)^\beta \quad \text{with } \beta < 1.
\]

The exponent \(\alpha\) is larger than unity because with increasing energy the \(N_e\) size at maximum grows linearly with energy while the shower maximum position approaches the detector level, while \(\beta\) is less than unity because muons are produced in the decay of mesons in processes such as \(\pi^+ \rightarrow \mu + \nu_\mu\), and the decay probability of high energy mesons is reduced because of the Lorentz time expansion. One can use equations (2) to express the muon number as a function of the \(N_e\) and the unknown mass \(A\) as:

\[
N_\mu \simeq K' \ A^{1-\beta/\alpha} \ N_e^{\beta/\alpha}
\]

with a mass dependence \(A^{1-\beta/\alpha} \sim A^{0.2}\), and the heavy primaries can in principle can be selected choosing muon rich showers. An example of this is shown in fig. 4 from the Kascade air shower experiment. The detector can measure simultaneously \(N_e\) and \(N_\mu\). In the bottom panel of fig. 4 the showers are selected in a fixed interval of \(N_e\), and the distribution in \(N_\mu\) is analysed to obtain the mass composition. Showers with a small muon number \(N_\mu\) are associated to proton primaries, while the highest \(\mu\) multiplicities are associated with iron nuclei. A quantitative analysis clearly requires a precise knowledge (including fluctuations) of the shower properties for primaries of different energy and mass. The results of fig. 4 have been fitted, using the QGSJET model, with a composition dominated by helium nuclei and smaller contributions of \(p, {^{16}\text{O}}\) and \(^{56}\text{Fe}\). It can be seen that the resolution in the measurement of \(A\) is not sufficient to separate the different components, and therefore the determination of the mass composition depends critically of the Montecarlo prediction, and one needs to consider a systematic error in the estimate of the energy spectrum and mass composition due to theoretical uncertainties in the modeling of shower development (that is in the description of the hadronic interaction properties). Similar considerations apply also to all other techniques for the determination of spectrum and composition in the knee region and above. For example the DICE experiment measures with two imaging telescopes the Cherenkov light produced by c.r. showers, obtaining two quantities per shower, then total number of Cherenkov photons \(N_{\text{Cher}}\) and the position of Shower maximum \(X_{\text{max}}\), showers with deep (shallow) \(X_{\text{max}}\) are attributed to protons (iron nuclei). The BLANCA detector operating in 1997–1998 measured the distribution of Cherenkov photons at the ground with a system of 144 angle integrating photon detectors, extracting two parameters per shower, the photon density at 120 meters from the shower axis \(C_{120}\).
and the exponential slope $s$ of the photon density in the 30–120 meters range ($\rho(r) \simeq K e^{-sr}$); steep (flat) slopes correspond to light (heavy primaries). The energy spectrum and composition can be obtained from the analysis of the distribution of events in the ($N_{\text{Cher}}, X_{\text{max}}$) or ($C_{120}, s$) planes\(^2\).

Some detectors can measure more than two quantities per shower, for example Kascade can measure not only the electron and muon sizes ($N_e$ and $N_\mu$), but also the hadronic component $N_{\text{had}}$ in its central calorimeter [20]. For a fixed energy, light primaries showers are more penetrating, and the hadronic component is larger. The analysis of the data in terms of different pairs of variables, for example ($N_e, N_\mu$) and ($N_e, N_{\text{had}}$), will give consistent results only if the modeling of the shower development is correct. Similarly (barring the existence of experimental systematic errors) the interpretation in terms of spectrum and composition of different experiments will be compatible only if the modeling of hadronic interactions is sufficiently accurate. This requirement of consistency (within and between experiments) allows in principle to obtain at the same time information about the spectrum and composition of primary c.r. and about the properties of hadronic interactions. This bootstrap philosophy has been at the center of considerable efforts in recent years (see for example [18] for a contribution at this conference). A critical analysis of all available data is beyond the scope of this summary (see [21,22] for a review and critical analysis). In a nutshell the main points are the following: (a) significant inconsistencies still exist within and between experiments, pointing to the necessity of an improved modeling of hadronic interactions; (b) a consistent picture is however beginning to emerge, the existence of the “knee” is firmly established, even if the precise shape and location are still uncertain may be by a factor as large as two, and most

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\(^2\)The “unfolding” of the spectrum and composition from the data is a non–trivial statistical problem, even under the assumption of no–systematical errors, and several approaches are possible. See for example the contributions of Kascade at this conference [18,19].
experiments extract a composition that becomes heavier across the knee, in agreement with the assumption of the knee as a rigidity dependent feature (see fig. 5 for an example); (c) the general features of the hadronic interactions incorporated in the Regge–Gribov models currently in use are at least qualitatively correct.

The energy region above the knee (10^{16} \leq E \leq 10^{18} \text{ eV}), is still relatively poorly known. The Kascade–Grande detector is planning to explore it, with the main aim to identify an “iron knee” at an energy $E \sim 6 \times 10^{16} \text{ eV}$ [23]. A detailed analysis of the size spectrum of 7 different air shower arrays [24] already gives some qualitative indications of the existence of a second knee, that could be attributed to the bending of the iron component. Some authors [25] see evidence as a more detailed structure in the knee energy spectrum, that are attributed to the contributions of a recent nearby supernova explosions.

The highest energy points in fig. 1 and 6 are from the Agasa [26] and Hires [27] detectors, the data of the Yakutsk array can be seen in [28]. The Agasa spectrum extends up to an energy $E \sim 3 \times 10^{20} \text{ eV}$. It is well known [29] that one expects the existence of a (Greisen–Zatsepin–Kuzmin or GZK) cutoff in the energy spectrum of cosmic rays due to interactions with the cosmic microwave background. The dominant process is pion photoproduction on the photons of the (2.7 K) Cosmic Microwave Background Radiation: $p + \gamma_{\text{CMBR}} \to p(n) + \pi + \ldots$, with an energy threshold of order $E_{\text{thr}} \simeq m_p m_{\pi}/\langle \epsilon \rangle \simeq \text{few} \times 10^{19} \text{ eV}$. Particles above the GZK cutoff should only arrive from near (on a cosmological case) sources. Since the $\gamma$ target is very precisely known and the interaction cross section has been accurately measured in experiments with protons at rest, it is possible to compute with very good precision the interaction length and energy loss of Ultra High Energy (UHE) protons. Similar considerations can also be made for composite nuclei, when the dominant energy loss process is photo-disintegration (such as $A+\gamma \to (A-1)+N$). The detailed shape of UHE cosmic rays flux will depend on the shape of the spectrum at the source (in particular on the maximum acceleration energy $E_{\text{max}}$), the distribution in space–time of the sources, and the structure of the extra–galactic magnetic fields, that control the propagation of charged particles from the source to our galaxy.

The energy determination of an EAS detector as Agasa (see [30] for a full discussion) is based on a measurement of the particle density at the ground at a distance \( \sim 600 \) meters from the shower core. It has been demonstrated [31] that this measurement is relatively insensitive to both the mass of the primary particle and the details of the interaction model, however in principle some model dependence is possible and needs to be very carefully investigated.

New results of the High Resolution Fly’s Eye, based on the fluorescence technique [27] show a spectrum that is well described assuming the existence of the GZK cutoff. In principle the measurement based of the detection of fluorescence light emitted by nitrogen molecules excited by the shower, represents a nearly completely model independent method for the energy determination. If $N(X)$ is the number of charged particle in a

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\[ \text{Figure 6. Recent measurements of the c.r. spectrum at the highest energy.} \]
shower at depth $X$ and $dY_{\text{flu}}/dE$ is the yield of fluorescence photons produced after the release of the energy $dE$ in ionization, then the number of fluorescence photons generated by the shower in the depth interval $(X, X + dX)$ is:

$$
\frac{dN_{\text{flu}}}{dX} = N_e(X) \left\langle - \frac{dE}{dX} \right\rangle \frac{dY_{\text{flu}}}{dE}(X)
$$

(4)

the $X$ dependence of the yield reflects a (strong) dependence on the air pressure. The number received at the detector, can be obtained from simple geometry (the fluorescence emission is isotropic) and a knowledge of the shower axis position if one has good control of the transparency of the atmosphere for the fluorescence photons. This technique in principle allows to measure the profile of the fluorescence emission along the shower axis, and therefore the profile of the shower energy loss, and by integration the total energy dissipated in ionization by a c.r. shower. The total energy of the primary particle can then be obtained applying small corrections for the energy that reaches the ground in the form of neutrinos, muons, hadrons and the tail of the electromagnetic shower. In this case the main sources of systematic uncertainties are the correct description of the fluorescence yield and of the atmospheric transparency.

### 2.1. Particles beyond the GZK cutoff ?

The question of the existence of a significant flux of particles particles with energy above the expected GZK cutoff is certainly the question that has attracted more excitement and controversy in cosmic ray physics in the last decade. In the following there is a list of possible solutions for this puzzle:

(i) There are no particles above the GZK cutoff. The present results of Agasa, Fly’s Eye, Haverah Park and other detectors are the effect of a combination of incorrect energy calibration, larger than predicted fluctuations in shower development, non-gaussian tails in measurements etc.

(ii) The highest energy particles are produced in few “standard” sources at small distances. The energy spectrum and the angular distribution expected in this scenario will then have strong features that should be clearly demonstrated with the higher statistics obtained from future experiments.

(iii) The highest energy particles are generated in the vicinity of our galaxy by the interactions of a more weakly interacting “carrier”. This is the so called “Z-burst” scenario \textsuperscript{32} where the carriers are ultra-high energy neutrinos. These neutrinos are created in “standard” sources, propagate in intergalactic space with negligible absorption, produce the observed UHE particles interacting with a postulated neutrino galactic halo. This scenario implies that there are neutrinos with energy $E_\nu$ at least a few times $E_{GZK}$ (and therefore at the source protons must be accelerated up to an energy several times $E_{GZK}$). To obtain a sufficiently large probability for interactions with the galactic halo this scenario assumes that the cross section is enhanced by the $s$-channel resonant production of $Z^0$ (the process $\nu + \overline{\nu} \rightarrow Z^0 \rightarrow \text{final state}$). This requires a neutrino mass of order

$$
\frac{M_Z^2}{2E_\nu} \sim \frac{M_Z^2}{(\text{few } 10^{21} \text{ eV})} \approx \text{few eV}
$$

(5)

that could be the correct number consistent with the existence of the halo.

(iv) The existence of UHE particles, coming from “invisible” sources can be naturally explained in the framework of the so called Top–Down models. In these models the UHE particles are not produced by acceleration (the Down–Top mechanism) but are the result of the decay of very large mass particles. The mass scale $M_X$ is related to a unification mass scale. In particular it is important to note that the grand–unification mass scale ($M_{\text{GUT}} \sim 10^{24} \text{ eV}$) is of the right order of magnitude so that the decay of particles with mass $M_X \sim M_{\text{GUT}}$ can produce the super–GZK particles. The Top–Down models require that the dark matter in the universe is provided by such super–heavy particles, or by topological defects (such as magnetic monopoles, cosmic strings, ...) that can decay into such particles.

(v) Finally one extraordinary possibility is the existence of violations of Lorentz invariance. In this case the GZK cutoff is not observed because it does not exist! The statement that protons of
energy $10^{20}$ eV produce pions interacting with photons of $\varepsilon \simeq 10^{-3}$ eV is based on the observations of the interactions properties of photons with $\varepsilon_{\nu} \sim 10^8$ eV with protons at rest, and on the assumption of Lorentz invariance and the validity of Lorentz invariance. The two frames are connected by a transformation with a Lorentz $\gamma$ factor of order $10^{11}$. If Lorentz invariance is violated the statement can become false. This apparently outrageous possibility is actually predicted in the framework of quantum gravity or in models where the space manifold has additional large extra dimensions.

It should be possible to determine which one is the true true solution of this puzzle thanks to the new detectors in construction (as Auger) or in the planning stage (as Euso) or based on the detection of fluorescence light from space.}

3. Cosmic Ray Astrophysics

A list of fundamental questions for c.r. astrophysics can be simply formulated as following:

(A) What if the dominant source for cosmic rays below the “knee”?

(B) What is the origin of the knee?

(C) What is the origin of the particles beyond the knee?

(D) At what energy the fluxes of extra–galactic and galactic cosmic rays are equal?

(E) Which are the sources of extra–galactic cosmic rays?

(F) Are there particles beyond the GZK cutoff?

It is surprising that we still do not have unambiguous answers to any of these questions. There is a general (but not universal) consensus that SuperNova Remnants (SNR’s) are the source of the galactic cosmic rays. This consideration is essentially based on two considerations: (i) SNR can provide the power ($L_{c.r.} \sim 10^{40}$ erg/s) needed to maintain the observed energy density of cosmic rays, taking into account the measured (rigidity dependent) confinement time of the cosmic rays; (ii) the mechanism of diffusive first order Fermi acceleration at a shock can naturally produce a power law source energy spectrum ($q(E) \propto E^{-\alpha}$) with a (differential) exponent $\alpha \simeq 2 + \varepsilon$ (with $\varepsilon$ small).

In diffusive shock acceleration a charged particle moving in a turbulent magnetic field of average strength $B$ performs “cycles” crossing back and forth across the shock discontinuity. During each cycle the particle acquires an energy $\Delta E \simeq 4/3 \beta_sh E$ (where $c_\beta_sh = v_2 - v_1$ is the difference between the velocity of the fluid on the two sides of the shock. The time for performing a cycle is of order $T_{cycle} \simeq D/(\beta_sh c^2)$, where $D$ is the diffusion coefficient that depends on the intensity and structure of the magnetic field. For a diffusion coefficient linear in $E$:

$$D \simeq \frac{1}{3} r_l c \simeq \frac{1}{3} \frac{E}{ZeB} c$$

the acceleration rate $dE/dt \simeq \Delta E/T_{cycle}$ becomes a constant, and the maximum energy obtainable is a Supernova can be estimated (using $R_{SNR} \sim cT_{SNR} \beta_sh$) as:

$$E_{max} \sim \frac{dE}{dt} T_{SNR} \sim R_{SNR} \times Z \times B \times \beta_sh$$

This energy is similar to the energy of the knee.

The simple “standard” scenario outlined above predicts an exponential cutoff of the cosmic ray flux at the maximum energy. This is very different from the simple moderate steepening of the energy spectrum observed in the data, and therefore the identification of the knee with the maximum energy in SNR remains unclear.

A problem that still waits for a clear answer is the determination of the energy at which the fluxes of galactic and extragalactic particles are equal. There is a general consensus that this energy must exist. The gyroradius of charged particles in a magnetic field is

$$R_{gyro} = \frac{p_\perp}{Z e B} \simeq 1.1 \frac{p_\perp (10^{18} \text{ eV})}{Z B (\mu\text{Gauss})} \text{ Kpc}$$

The galactic radius is $r_{gal} \sim 15$ Kpc, and the typical strength of the magnetic field is $B \sim 3 \mu\text{Gauss}$, therefore very likely the highest energy cosmic ray cannot remain confined inside the Galaxy. It is possible that the energy where the fluxes of particles of galactic and extra–galactic origin are equal corresponds to the so called “ankle” ($E \sim 10^{19}$ eV) in the c.r. spectrum, however it is also claimed that the ankle is an
assorption feature due to the process $p + \gamma_{cmb} \rightarrow p + e^+ + e^-$ and that the crossing point for the two population is at lower energy. This is clearly an important point that can be clarified with additional data on the energy spectrum and angular anisotropy of cosmic rays.

Equation (7) can be used to constraint the size and magnetic field of any source of cosmic rays where the acceleration mechanism is first order Fermi acceleration. This implies that very few objects in the known universe can have a sufficiently large product $R_{source} \times B$ to be a candidate for the acceleration of the UHE cosmic ray [38]. AGN and GRB are perhaps the best candidates for this purpose.

4. Hadronic Interactions

The study of high energy cosmic rays requires “indirect methods” that is the measurement of the shower produced by the primary particle. The uncertainties in the prediction of the development of the shower produced by a primary cosmic ray are the consequence of uncertainties in the calculation of hadronic interactions. The problem is the following: one has a “projectile” particle (a proton, a nucleus (A,Z), or a weakly decaying meson such as a pion or kaon) and one needs to know the interaction cross section with the air nuclei (mostly nitrogen and oxygen), and the properties of the final state produced in such an interaction, namely the multiplicity, flavor composition and momentum distribution of the final state particles, with a correct estimate of the fluctuations. It is well known that now and for the foreseeable future we are not in the condition to compute from first principles these needed quantities from the fundamental QCD Lagrangian. Moreover the existing data do not cover all the “phase space” necessary for purely phenomenological description. The c.m. energy on nucleon–nucleon interactions for cosmic rays in the knee region ($E \sim 3 \times 10^{15}$ eV) and near the GZK cutoff energy ($E \sim 10^{20}$ eV) are:

\[
\begin{align*}
(\sqrt{s_{NN}})_{knee} & \sim 2.5/\sqrt{A} \text{ TeV} \\
(\sqrt{s_{NN}})_{GZK} & \sim 400/\sqrt{A} \text{ TeV}
\end{align*}
\] (9)

(A is the mass of the primary particle). The highest energy collisions produced in an accelerator have $\sqrt{s_{pp}} \simeq 1.8$ TeV at the Tevatron, and therefore corresponds closely to the knee; the LHC collider at CERN will reach $\sqrt{s_{pp}} \simeq 14$ TeV, that is still approximately 30 times lower than the GZK energy. However the situation is much worst than what appears from these simple considerations. The measurements at the hadron colliders have been limited to an angular region that excludes the beam pipe, and therefore a very large majority of the high energy particles that are emitted at small angles are unobservable (see fig. 9). These particles carry more than 90% of the energy in a collision and are clearly those crucial in determining the properties of air showers. It should also be noted that the study of hadron–nucleus interactions is still limited to fixed target energies ($\sqrt{s_{NN}})_{AA} \lesssim 0.27$ TeV). The new data from the RHIC detector about gold–gold detector at ($\sqrt{s_{NN}})_{AA} \lesssim 0.2$ TeV) presented at this conference by S. Klein [39] have therefore great value in testing the accuracy of the treatment of nuclear effects used in the existing montecarlo codes. In fact a comparison has shown the existence of non–trivial discrepancies (15–20% in the central region rapidity density, see [10,11,12]).

At fixed target energies the inclusive distribution of final state particles exhibit in first approximation the property of Feynman scaling:

\[
\frac{d\sigma_{pp\rightarrow a}}{dp_{\parallel} d^2p_{\perp}}(p_{\parallel}, p_{\perp}, \sqrt{s}) \simeq f_a(p_{\parallel}, \sqrt{s}) G_a(p_{\parallel}) \simeq \frac{F_a(x_F)}{E} G_a(p_{\perp})
\] (10)

where $x_F = 2p_{\parallel}^*/\sqrt{s}$ and the functions $F_a(x_F)$ and $G_a(p_{\perp}) \propto e^{-bp_{\perp}^2}$ are independent from $\sqrt{s}$. Clearly the assumption of Feynman scaling allows to extrapolate the low energy results and to predict the properties of showers of arbitrary energy. However the data of the hadron colliders (ISR, SppS, Tevatron and RHIC) have shown that Feynman scaling is violated. As an example the scaling function $F_\pi$ for pion production in $pp$ interactions has approximately the form $F_\pi(x_F) \simeq C (1 - |x_F|^n)$ with $n \sim 3–4$. This form indicates that pions are approximately produced
with a spectrum $dn/dE \sim 1/E$ peaked at low energy. At collider energy the quantity $C$ (that is the value of $F_\pi$ near $x_F \sim 0$ or the height of the rapidity plateau) is measured to grow logarithmically with increasing $\sqrt{s}$. The form of scaling violations for large $|x_F|$ (for nucleons and mesons) is known much more poorly, however it is essential for shower development.

The spectrum of the nucleons produced in hadronic interactions plays a fundamental role in the development of c.r. showers. At fixed target energy a fraction $\sim 20\%$ of the $pp$ inelastic interactions is due to “single diffraction” where one if the incident protons is excited into a state $X$ with the same internal quantum numbers that scatters elastically with small transfer momentum with the other proton and $\sim 5\%$ of the inelastic interactions can be attributed to double diffraction). Note that in a target diffraction event the projectile proton retains nearly all the initial energy, while in projectile diffraction, the decay of the excited state $X$ result in a final state nucleon that carries a very large fraction ($\gtrsim 50\%$) of the initial $p$ energy. In non–diffractive interactions the final state nucleons have a hard–spectrum ($dn/dE \sim \text{const}$) and carry approximately $\sim 40\%$ of the initial state energy\footnote{Traditionally the energy fraction carried by nucleons has been called by comsnc ray physicists the “elasticity” of the interaction.}. These high energy nucleons in the final state feed energy deeper into the shower and clearly play a very important role in the shower development. At the hadron colliders most of these nucleons are unobserved, and their spectrum must be inferred with a large amount of uncertainty.

4.1. Montecarlo Modeling

A general framework to compute the properties of hadronic ($hp$, $hA$ and $AA$) interactions has been developed in the last 10 years [13]. In this framework, the so called “Regge–Gribov effective theory”, that is formally very similar to an eikonalized parton model, an hadronic collision is analysed as a set of sub–interactions, or “Pomeron exchanges”, between the participant particles. A fraction of these sub–interactions can be simply understood as hard or semi–hard interactions between partons, that can be treated in perturbative QCD, while another fraction is “soft”. The growth of the cross section with energy is related to the increase of the number of sub–interactions with increasing $\sqrt{s}$. This approach can be naturally implemented into montecarlo algorithms. The “topological structure” of one event, that is the number and type of sub–interaction is translated into the formation of a set of color strings (closed loops or objects with $q$, $\overline{q}$ or $qq$ “endings”) conserving exactly 4–momentum and all quantum numbers. These strings are then fragmented into observable hadrons using algorithms similar (or identical) to the algorithms developed by the LUND group. Several montecarlo implementation of this philosophy (QGSJET, Sibyll, DPMJET, VENUS, NEXUS) have been developed and are used in the montecarlo simulation of c.r. showers. A discussion of the differences between these MC implementations can be found in [13].

It is encouraging that the differences between the latest versions of the models are smaller than in the past. The size of these differences has been used to estimate the importance of systematic uncertainties in hadronic interactions modeling. It should be noted that the use of this method has the danger to underestimate systematic errors, because all of these codes share the same basic theoretical assumptions, and therefore naturally converge to similar results. It should not be forgotten that despite of their sophisticated language the theoretical basis for this models is not rock solid, and significant uncertainties still exist. In fact several important problems do not have an unambiguous answer in the framework of the Regge–Gribov approach. In particular it is not clear how diffraction fits in the theoretical scheme; there is also significant arbitrariness in the shape (and evolution with energy) of the inclusive particle distribution in the fragmentation regions ($|x_F| \gtrsim 0.1$). It is significant that each time new accelerator data has become available (from ISR to the recent RHIC data) significant differences with the available predictions were found. New data is clearly required to validate (or correct) the existing models.
4.2. NEEDS: Requests of cosmic ray physics to accelerator physics

For a full and correct interpretation of the cosmic ray shower measurements at and above the knee new data from accelerator experiments are required. The cosmic ray community has invested significant efforts in the “bootstrap method” (extracting the cosmic ray energy spectrum and composition together with the main features for hadronic interactions purely from cosmic ray shower measurements), and important theoretical efforts are made to construct well motivated extrapolations of the existing data into the required phase space region ($\sqrt{s}, x_F, p_\perp$); however there is a broad consensus in the community that the best perspectives for progress in improving energy and mass resolutions is new data from accelerators. A workshop (opportunistly named “NEEDS”) was held in Karlsruhe in April 2002 to discuss which measurements of hadronic interaction properties are most important for the field, and how it is possible to obtain them. This discussion continued at the ISVHECRI conference (see for a review and discussion).

Some central questions are:
(i) How important are the uncertainties in our knowledge of hadronic interactions in the determination of the cosmic ray flux and composition?
(ii) What impact can have the planned future experiments in reducing these uncertainties?
(iii) Which additional experimental programs can help in further reducing these uncertainties?

A brief list of the most important measurements for shower development could be:
(i) Precise measurements of total and inelastic cross section.
(ii) Measurements of the ratio $\sigma_{\text{diff}}/\sigma_{\text{inel}}$.
(iii) Energy distribution of the leading nucleon in the final state.
(iv) Inclusive pion spectra in the fragmentation region $x_F \gtrsim 0.1$.

The optimum would clearly be to have these measurements for $pp$, $pA$ and $AA$ collisions at the LHC collider.

5. Emulsion Chambers results

The Emulsion Chamber technique, developed in the Chacaltaya laboratory in Bolivia ($h = 5200$ m) has been in use for more than 30 years in laboratories placed at mountain altitude. The basic structure of an emulsion chamber is a sandwich of absorber (lead) layers alternated with sensitive (emulsion or X-ray film) layers as illustrated in fig. A chamber (with typically a surface of order $10 \, \text{m}^2$) is exposed for a time interval of several months, then the sensitive layers are removed, developed and analysed. A charged particle crossing a sensitive layer leaves a track that is visible with a microscope; a shower composed of many nearly parallel and closely packed particles leaves a dark spot. The darkness is measured with photometers analysing the transparency of the sensitive layer around that position. Spots corresponding to the same shower can be associated with each other obtaining a ‘longitudinal darkness profile’ for a shower, and from it an estimate of its electromagnetic energy. The detection threshold for a shower depends on the sensitive material used and the level of background present, and is typically ~ 1 TeV. At this energy the spot of a shower at maximum is visible with naked eyes, and the scanning process is much simplified. The interaction length in lead ($\lambda_{\text{int}} \approx 18.5 \, \text{cm}$) is much longer than the radiation length ($X_0 \approx 0.57 \, \text{cm}$), therefore an emulsion chamber effectively measures only the electromagnetic component of a shower. Because of the large difference between $\lambda_{\text{int}}$ and $X_0$, photons and charged hadrons arriving to the chamber can be clearly separated, since $\gamma$-induced showers initiate after one radiation length (in practice after the first absorption layer), while hadron showers initiate after one interaction length (that is several absorber layers). In many chambers, to enhance the hadron detection efficiency, the emulsion chamber is divided into two parts with in the middle a low $Z$ material (for example carbon) target layer where hadrons can interact generating photons (via $\pi^0$ decay) that are then detected in the lower chamber. For hadron–induced showers, only the energy fraction that goes into $\pi^0$ production in the first interaction ($\sim 0.2$ of the ini-
tial energy for a $p$) is visible in the chamber. A primary particle interacting above the detector will produce several secondaries, the high energy ones that reach the emulsion chamber generate a bundle of close spots due to the quasi–parallel showers that are collectively called a “family” (see fig. 8). The showers of a family can be analysed together to obtain information about the nature of the primary particle, and about its interaction properties. In some cases it is possible to deduce the position of the primary interaction point by triangulation as the point where the sub–shower axis converge. Clearly the emulsion–technique is a very interesting method to study with very fine resolution the core of high energy cosmic ray showers.

For a long time there have been claims of the existence of unusual events in the emulsion chambers. The most well known and most interesting type of these “exotic” events are the “Centauros”. A “Centauro” is an event (a family) here a large fraction of the total visible energy is attributed to hadron showers. For example the celebrated Centauro–1 event detected 30 years ago in Chacaltaya laboratory was composed of 49 hadron showers and only one $e/\gamma$ shower. A small number of Centauro candidates has been obtained by the Chacaltaya and Pamir collaboration while no events have been found at Mount Fuji and and Mount Kambala.

Thirty years of investigations have not clarified the nature of the centauro phenomenon. Possible interpretations fall into two categories: exotic primaries (such a compressed glob or hadronic matter or a strangelet), or the result of new features of hadronic interactions at high energy, such as the formation of “disoriented chiral condensate”. Also the possibility that the events have an explanation in terms of standard physics, fluctuations and selection effects cannot be disregarded. All type of explanations run into significant difficulties. Searches for centauro–like events at accelerators, including the recent RHIC data have been negative. These negative results cannot completely eliminate the interpretation of Centauro events as a feature of the hadronic interactions, because not the entire relevant phase

\[
N = \text{number of showers in a family} \quad Q_h = \frac{E_h}{E_h + E_{\gamma}} = \frac{\text{fraction of the reconstructed energy attributed to hadrons}}{\text{total reconstructed energy}}
\]

depends on the exact definition of “centauro”. Experimentally centauro candidates fall in the region of large $N$ and large $Q_h$, in the plane $(N,Q_h)$ where $N$ is the number of showers in a family and $Q_h = E_h/(E_h + E_{\gamma})$ is the fraction of the reconstructed energy attributed to hadrons). Depending of the cuts applied the world sample of Centauro candidates is of order $\sim 5–10$. It has not been clearly established if they constitute a distinct population or are the tail of a single distribution that fills the entire $(N,Q_h)$ plane.
space has been covered. A new specialised detector CASTOR (within CMS) \[52\] (covering the very forward pseudorapidity region \[5.5 \leq \eta \leq 7\]) has been proposed to search for the centauro phenomenon at LHC.

It is important to note that several scientists working with emulsion chambers, and in particular S.A. Slavatinsky \[53\] argue that the data on primary particles with an estimated energy \(E \gtrsim 10^{16} \text{ eV}\) exhibit features that cannot be explained in the framework of the standard model. One of these features is the existence of coplanar emission \[54\] (that is families where the particles form approximately a straight line), another one is the indication of the existence of very strong Feynman scaling violations in the forward fragmentation region. The conclusion that the emulsion chamber results in the energy range 10–100 PeV indicate new unexpected effects remain very controversial and requires further analysis.

The emulsion chamber technique has now been in use for over three decades, and remains a remarkable tool to study with excellent resolution the core of high energy showers. The data obtained with these detectors has given indications of unusual phenomena, that remain controversial and unexplained. An important open question is the future of these studies, and how to solve the puzzles they have suggested. Further progress requires either a significant increase in the exposures of the detectors (implying larger areas and faster analysis methods), or the introduction of new innovative experimental methods to study the hadronic core of showers. An interesting new idea for an hadronic core detector is being developed by the Tibet shower array \[55\].

6. CERN: Opportunities and Challenges

6.1. Cosmic Ray Measurement at CERN

At least three of the LEP experiments at CERN have taken data on cosmic rays not only for the purpose of calibration, but in order to do measurements. The L3 detectors \[56\] has used the inner detector to measure the inclusive muon momentum spectrum in the range 15–2000 GeV. This measurement is important to constraint the calculation of the atmospheric neutrino fluxes in a similar range, since both \(\mu\)'s and \(\nu\)'s are produced in the decay of the same primary mesons (\(\pi^\pm\)'s and Kaons). The L3 detector has also taken data in coincidence with a small shower detector at the surface (the L3+C configuration) \[57\]. Multiple muon events have also been measured by the Aleph \[58\] and Delphi \[59\] detectors. Some events are spectacular containing more than 100 parallel muons. These events are produced by primary particles in the range \(10^{14} \sim 10^{16} \text{ eV}\), and therefore a detailed study can provide information about the spectrum and composition of cosmic rays in the knee region. These measurements are valuable especially in combinations with other measurements of showers in the same energy range, and in the spirit of the “bootstrap” philosophy discussed above.

6.2. LHC and cosmic ray physics

The CERN LHC project (a 7+7 TeV \(pp\) collider with options for \(p\)-nucleus and nucleus–nucleus collisions) has a compelling and ambitious program that is clearly of central importance for the development of fundamental science \[60\]. Four detectors (ATLAS, CMS, LHC-b and ALICE) will explore the physics at LHC, LHC-b is dedicated to the physics of the \(b\)-quark, ALICE to the study of heavy–ion physics, ATLAS and CMS are optimized for the study of high \(p_{\perp}\) interactions between quark and gluons, and the production of heavy particles like the Higgs or the supersymmetric particles.

The essential contribution of CERN to cosmic ray physics is related to the more precise measurements of hadronic interaction properties at high origin, and the LHC project can play a fundamental role. The motivation is clear: in future studies of cosmic ray physics, very high energy particles will certainly have central importance, these particles will be detected with indirect methods, and the precision and resolution of the measurements of the energy and mass (or identity) of the primary particles will depend on the knowledge of hadronic interactions at a c.m. energy as high as 400 TeV. Measurements that are only possible at LHC have the potential to significantly improve the quality of these measurements, in the “knee region” and especially for the very high energies.
\( E \gtrsim 10^{19} \text{ eV} \)\(^6\)

If the existence of a relatively large flux of particles beyond the GZK cutoff is confirmed, this nearly certainly implies the existence of “new physics” and the detailed study of particles above the expected cutoff will clearly become one of the most important fields of experimental studies in fundamental physics, however this conclusion remains valid even in the “conservative” scenario, where the flux exhibits the expected cutoff and all cosmic rays have a “standard” origin. In this case the precise measurement of the energy distribution and composition (together with the angular distribution) of particles at the “end of the spectrum” will be essential to obtain information about the nature, location and time evolution of the cosmic accelerators (that are certainly going to be some of the most interesting objects in the universe).

6.3. Cross section measurements at CERN

Of particular importance for cosmic ray physics is the measurement of the total and inelastic cross section. The Totem experiment \(^6\) (designed together with CMS) will provide measurements of the total cross section (with a precision of 1\%), elastic scattering and diffractive processes at the LHC. The total cross section will be measured using the luminosity independent method which based on the simultaneous detection of elastic scattering at low momentum transfer and of the inelastic interactions. One can use the optical theorem:

\[
\sigma_{\text{tot}} = \frac{4\pi}{p_{\text{c.m.}}} \Im[f(0)]
\]

where \( f(\theta) \) is defined by:

\[
\frac{d\sigma_{\text{el}}}{dt} = \frac{\pi}{p_{\text{c.m.}}^2} \frac{d\sigma_{\text{el}}}{d\Omega_{\text{c.m.}}} = \frac{\pi}{p_{\text{c.m.}}^2} |f(\theta)|^2
\]

and the definition of the total cross section:

\[
\sigma_{\text{tot}} = (\sigma_{\text{el}} + \sigma_{\text{inel}}) = (N_{\text{el}} + N_{\text{inel}})/\mathcal{L}
\]

(where \( \mathcal{L} \) is the integrated luminosity) to extract the total cross section independently from the luminosity as:

\[
\sigma_{\text{tot}} = \frac{16\pi}{1 + \rho^2} \left[ \frac{dN_{\text{el}}/dt}{t} \right]_{t=0}/(N_{\text{el}} + N_{\text{inel}})
\]

where \( \rho = \Re[f(0)]/\Im[f(0)] \approx 0.15 \) is the ratio of the real and imaginary part of the elastic scattering amplitude. The difficulty of this measurement is to obtain a good extrapolation of the cross section for a transfer momentum \( t \to 0 \). Since \( -t = -(p_i - p_f)^2 \approx 2p_{\text{c.m.}}^2 (1 - \cos \theta) \approx p_{\text{c.m.}}^2 \theta^2 \), this implies the measurement at very small angle. The Totem experiment aims to a measurement down to a values \( -t \approx 2 \times 10^{-2} \text{ GeV}^2 \), that corresponds to \( \theta \approx 20 \text{ mrad} \), that is a displacement of 3 millimeters at a distance of 150 meters from the interaction point. The measurement is possible with the use of the so called “Roman pots”\(^7\) placed symmetrically on both sides of the intersection region to detect protons scattered at very small angles in elastic or quasi-elastic reactions. A forward inelastic detector covering about 4 pseudorapidity units in the forward cones (from \( \eta = 3 \) up to \( \eta = 7 \)) with full azimuthal acceptance will be used to measure the rate of inelastic reactions. Totem has also the potential to measure diffractive interactions. As discussed before a determination of \( \sigma_{\text{diff}}/\sigma_{\text{inel}} \) is very important for shower development.

6.4. Acceptance limitations and “soft” hadronic physics

There are compelling reasons to expect that the most interesting physics at LHC will involve small cross sections (for example the Higgs production cross section is expected to be a fraction of order \( 10^{-10} \) of \( \sigma_{\text{inel}} \), and will manifest itself with particle (jet) production at large \( p_\perp \) and therefore at relatively large angles with respect to the beam axis. The ATLAS and CMS detectors are primarily designed to study this type of processes, and their acceptance is limited to the angular (pseudorapidity) region \( |\eta| \leq 2.5 \) \((\theta \leq 9.3^\circ)\).

\(^6\)An important task for the c.r. community is to quantify more precisely the improvement obtainable with different measurements at the LHC.

\(^7\)The Roman pots are special devices mounted on the vacuum chamber of the accelerator. They can be retracted to leave the vacuum chamber free for the beam as required at the injection. Once the final energy is attained and the circulating beams are stable, they can be moved close (\( \sim 1 \text{ mm} \)) to the beam.

\(^8\)The pseudorapidity is defined as \( \eta = -\ln[\tan(\theta/2)] \). For a massless particle it coincides with the rapidity \( y \) defined
for charged particle detection, and to $|\eta| \leq 5$ ($\theta \leq 0.77^\circ$) for calorimetric energy flow. As discussed before the Totem detector will cover the region $3 \leq |\eta| \leq 7$. Fig. 9 illustrates the region of $x_F$ and $p_{\perp}$ that corresponds to these angular acceptances. It is clear that these detectors will give only poor results about particle production in the fragmentation regions $|x_F| \gtrsim 0.1$. We expect that most of the energy of the minimum—bias interactions ($> 90\%$) will remain unobserved with the detectors under construction.

The design (and construction) of a full—acceptance detector for LHC is an extraordinarily difficult (and costly) task. A detailed project for such a detector has been elaborated by the Felix collaboration [62]. The scientific motivations for such a full (or very large) acceptance detectors are also extensively discussed in [62]. While there is a consensus that the scientific priority for the LHC science is in the large $p_{\perp}$ region, there are strong (even if less compelling) arguments for a significant discovery potential exist also for detectors that cover a larger angular region. On the point of view of cosmic ray studies there is considerable interest in having as large an acceptance as possible. The fragmentation region that plays a crucial role in shower development corresponds to the pseudorapidity range $6 \lesssim |\eta| \lesssim 10$. The possibility to explore, even partially, a broader phase space region at LHC upgrading the approved detectors certainly deserves to be investigated energetically.

7. Conclusions

The next decade looks very interesting for cosmic ray studies, in fact it is possible that finally an understanding of the main sources of the high energy radiation in the universe will be obtained. This understanding will be the result of a large experimental effort, including direct and indirect measurements of cosmic rays. For a correct interpretation of the EAS shower measurements the contribution of accelerator experiments will be of great importance, in the entire energy range between $10^{15}$ and $10^{20}$ eV. The desired measurements at LHC are not easy to perform, and an optimum program would require a larger acceptance coverage and therefore additional costly instrumentation; it can however be argued that these measurements are not only of relevance for cosmic ray research but have also a significant intrinsic interest and the potential for scientific discovery, and deserve careful analysis.

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REFERENCES

1. J. Ellis, these proceedings.
2. T. Kamae, these proceedings.
3. L. Resvanis, these proceedings;
   H. Athar, these proceedings.
4. BESS Collab., Astrophys. J. 545, 1135 (2000) [astro-ph/0002481].
5. AMS Collab., Phys. Rept. 366, 331 (2002).
6. Caprice Collab., astro-ph/0212253
7. M. Pohl, these proceedings.
8. E. Bugaev, these proceedings.
9. Jacee Collab. Ap.J. 502, 278 (1998).
10. RUNJOB Collab., Proceedings of 26th ICRC, vol.3, 165 (1999).
11. J. J. Beatty et al., Proc. of 26th ICRC OG.4.1.16 (v.5, p.61) (1999).
12. T.K. Gaisser, T. Stanev and P. Lipari, Proceedings of 27th ICRC, Hamburg (2001).
13. H. Ulrich, these proceedings.
14. Antonella Castellina, these proceedings, EASTOP Collab., Astrop.Phys, 10, 1, (1999);
15. D. Heck, these proceedings; D. Heck, M. Risse and J. Knapp, astro-ph/0210392.
16. D. B. Kieda and S. P. Swordy, in Proc. 26th ICRC (1999).
17. M. Cassidy et al., astro-ph/9707038.
18. A. D. Erlykin and A. W. Wolfendale, these proceedings [hep-ph/0210129].
19. M. Roth, these proceedings.
20. J. Mielke, these proceedings.
21. S. P. Swordy et al., Astropart. Phys. 18, 129 (2002) [astro-ph/0202159].
22. K.H.Kampert, astro-ph/0212348.
23. K.H.Kampert, these proc., astro-ph/0212347.
24. G. Schatz, these proceedings and Astropart. Phys. 17, 13 (2002) [astro-ph/0104282].
25. A. D. Erlykin and A. W. Wolfendale, these proceedings and J. Phys. G 27, 1005 (2001).
26. N. Hayashida et al. [Agasa Collab.], Astrop. Phys. J. 522, 225 (1999).
27. Hires Collab., astro-ph/0208243.
28. A. V. Glushkov et al. [Yakutsk Collab.], Phys. Atom. Nucl. 63, 1477 (2000) [Yad. Fiz. 63, 1557 (2000)].
29. M. Nagano and A. A. Watson, Rev. Mod. Phys. 72, 689 (2000).
30. M. Takeda et al. (Agasa Collab.), astro-ph/0209422.
31. M. Hillas, Proceedings 12th ICRC (Hobart), vol.3, 1001 (1971).
32. D. Fargion, B. Mele & A. Salis, Ap.J. 517, 725 (1999) [astro-ph/9710009]; T.J. Weiler, Astrop. Phys. 11, 303 (1999); [hep-ph/9710431].
33. P. Bhattacharjee and G. Sigl, Phys.Rep. 327, 109 (2000) [astro-ph/9811011].
34. G. Amelino-Camelia et al., Nature 393, 763 (1998) [astro-ph/9712103].
35. M.T. Dova, these proceedings.
36. L. Scarsi, these proceedings.
37. V. Berezinsky, A. Z. Gazizov and S. I. Gridneva, hep-ph/0204357.
38. A.M. Hillas, Ann.Rev.Astr. A. 22, 425 (1984).
39. S. Klein, these proc., astro-ph/0211018.
40. J. Ranft, these proceedings.
41. R. Engel, these proc., [hep-ph/0212340].
42. K. Werner, H. J. Drescher, S. Ostapchenko and T. Pierog, hep-ph/0107170.
43. www-ik.fzk.de/~needs/.
44. S. Ostapchenko, these proceedings; R. Engel, [hep-ph/0111396].
45. J. Knapp, these proceedings.
46. C. M. Lattes, Y. Fujimoto and S. Hasegawa, Phys. Rept. 65, 151 (1980).
47. L. T. Baradzei et al. [Chacaltaya Collab.], Nucl. Phys. B 370, 365 (1992).
48. A. Ohsawa, these proceedings; E.H.Shibuya, these proceedings; V.M. Maxineko, these proceedings.
49. K. Alpgard et al. [UA5 Collab.], Phys. Lett. B 115, 71 (1982); G. J. Aner et al. [UA5 Collab.], Phys. Lett. B 180, 415 (1986).
50. G. Arnison et al. [UA1 Collab.], Phys. Lett. B 122, 189 (1983).
51. J. D. Bjorken and L. D. McLerran, Phys. Rev. D 20, 2353 (1979).
52. A. Angelis, these proceedings.
53. S. A. Slavatinsky, these proceedings, Nuovo Cim. 24C, 557 (2001); Nucl. Phys. Proc. Suppl. 97, 109 (2001).
54. A.S. Borisov, these proceedings.
55. L.K. Ding, these proceedings.
56. P. Le Coutre, these proceedings; O. Adriani et al., Nucl. Instrum. Meth. A 488, 209 (2002).
57. H. Wilkens, these proceedings.
58. cosmolep.web.cern.ch/CosmoLep/.
59. P. Travnichek, these proceedings.
60. Fabiola Gianotti, these proceedings.
61. K. Eggert, these proceedings.
62. Agreev et al., J. Phys. G 28, R117 (2002).