High-Energy Interactions and Extensive Air Showers

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ABSTRACT

In this report a summary of recent developments in the fields of high-energy nuclear interactions (HE 1) and air shower phenomenology (HE 2) is presented. New results from accelerator and cosmic-ray experiments and the progress in the theoretical understanding and simulation are reviewed and their impact on air shower analysis is discussed.

1 Introduction

The main astrophysical questions related to high-energy cosmic rays (CR) are those for the source and the acceleration mechanisms of CR and the origin of the knee in the all-particle spectrum. These questions can only be addressed if the mass and the energy of the CR arriving on Earth can be determined. Unfortunately, cosmic radiation at energies above $10^{15}$ eV can presently only be investigated by studying of extensive air showers (EAS) which are produced by subsequent interactions of the primary particles with the nuclei in the atmosphere. Thus, the mass and the energy of the primary particle are deduced from the measurable properties of the EAS.

The shower development depends on the primary mass and energy. However, it is influenced by the properties of the hadronic and electromagnetic interactions and by the mechanisms of the transport of secondary particles through the atmosphere as well. Especially the hadronic and nuclear interactions impose large uncertainties since they are only poorly known in the energy and kinematic ranges of interest. In addition, a detector with its limited acceptance and efficiency gives a distorted picture of the secondary particles from which the EAS properties have to be reconstructed.

The challenge of experimental EAS physics is to understand the shower development and the detector performance well enough to enable a reliable reconstruction of the mass and the energy of the primary particles starting from the measured energy deposits and time signals in the single detector elements without being able to calibrate the experiment in a suitable test beam with well-known energy and mass composition.

In this article we try to highlight the recent developments in the understanding of high-energy interactions, air shower development, and reconstruction algorithms and discuss the implications on the interpretation of experimental findings.

2 New Results from Accelerator Experiments

2.1 Heavy Ion Collisions

In the first collision of a CR particle with an air nucleus, a projectile nucleus (p, He, C, ... Fe) with energies of several TeV up to $10^{20}$ eV hits a target nucleus (N, O, Ar) with a random impact parameter. Projectile and target are divided into so-called participant nucleons, which

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are actively involved in the collision, and spectator nucleons, which move on with their initial velocity. The participant nucleons contribute part or all of their energy to form a fireball leading to the production of secondary particles, while the spectators form remnant nuclei in more or less exited states that consequently stabilize in a nuclear fragmentation process. Most collisions are peripheral with only few nucleons of projectile and target participating, few are central with much energy involved in the particle production.

This kind of reactions is traditionally investigated in heavy ion collisions, however, at much lower energies. At CERN measurements have been performed with Pb nuclei of $E = 158$ GeV/n and at Brookhaven with Au nuclei of 10.6 GeV/n colliding with various targets. New results on nuclear fragmentation [51, 81, 80, 37] and on particle production [23] have been reported. The fragmentation of the projectile remnant is of special importance for CR physics because in case of an air shower it carries a big part of the primary energy through the atmosphere and, hence, influences the further shower development. The KLM Collaboration, e.g., measured the emerging fragments by means of lead-emulsion chambers with good spatial and charge resolution and presented the distributions of the total charge of multicharged ($Z > 2$) fragments in Au-H, Au-(C,N,O), Au-(Ag,Br), and Pb-Pb interactions [81]. They found more smaller fragments for more symmetric projectile-target systems and for heavier targets. In 10.6 GeV/n Au-emulsion collisions [80] a characteristic dependence of the distribution of the total charge bound in fragments ($\sum Z$ with $Z > 2$) on the average transverse momentum $\langle p_\perp \rangle$ is observed. Events with $\langle p_\perp \rangle > 90$ MeV/c coming from more central collisions exhibit basically a flat distribution of $\sum Z$ while events with $\langle p_\perp \rangle < 90$ MeV/c from peripheral interactions show a pronounced peak at $\sum Z = 65...80$ because in peripheral collisions a big projectile survives. Those distributions, depending on energy and on the mass of projectile and target, are important to check and tune the models being employed for relativistic nuclear reactions.

The production of secondary particles in the central collision zone is investigated in Ref. [23]. Their distribution in pseudorapidity $\eta = \frac{1}{2} \ln \frac{p_\perp + p_T}{|p_\perp| - p_T} = - \ln \tan(\theta/2)$, which basically represents the emission angle of the particle to the beam, is compared to calculations with the FRITIOF [68, 5] and the VENUS [79] model. The latter model allows for interactions of secondaries particles with spectators or with each other in case of large multiplicities leading to a redistribution of particle energies and a better agreement with experimental data at lower energies and with lower projectile and target masses [79]. Re-interactions become more important for higher energy densities, i.e. larger nuclei and more central collisions. In Pb-Pb collisions, however, it turns out that all models overestimate the central pseudorapidity density by 30 to 50% and VENUS without re-interaction agrees better with the data than VENUS including it. These findings indicate that the description of particle production in the models still is to be improved for heavy nuclei.

2.2 HERA Results

Events with high $p_\perp$ secondaries or jets become more important with increasing energy. While low $p_\perp$ secondaries still dominate by far, the tail of high $p_\perp$ particles is growing with energy, giving rise to the so-called minijets with $p_\perp$ in the few GeV range. The rise of the cross-section for minijet production is strongly dependent on the structure of the nucleon, since with increasing energy more and more low-energy partons of projectile and target can contribute to inelastic collisions. Gluons dominate due to their vanishing restmass at low parton energies. The distribution of parton momenta $x = p_{\text{parton}}/p_{\text{total}}$ inside a nucleon is described by the structure function $F_2$ which was measured recently at the HERA $e$-p collider for different momentum transfers $Q^2$ down to $x \approx 10^{-5}$ (see e.g. Ref. [1]). Fig. 2 shows that the experimental results from the H1 experiment are in good agreement with parameter-free calculations from first QCD principles by Glück, Reya, and Vogt [39] and several other calculations. These structure
functions for the first time allow to calculate the minijet cross-sections up to highest cosmic-ray energies on a reliable theoretical basis and should be implemented in all high-energy hadronic interaction generators.

2.3 p-¯p Collider Experiments

The MINIMAX experiment [52] at the Fermilab collider was designed to measure secondaries in very forward direction at a pseudorapidity of \( \eta = 4.1 \pm 0.3 \). Its primary physical goal is the search for disoriented chiral condensates (DCC) [13] which manifest themselves by large fluctuations in the fraction \( f = N_{\pi^0}/(N_{\pi^0} + N_{\pi^\pm}) \) of \( \pi^0 \)s produced in an interaction. For DCC the distribution of \( f \) is proportional to \( 0.5/\sqrt{f} \) and not binomial as predicted by standard interaction models (see Fig. 3). Therefore, DCC have been discussed as a possible source of Centauro-type events. These are events with a large number of hadrons and a comparatively small number of photons. Centauro-type events have been detected by several emulsion chamber experiments and are interpreted as an indication of new physics in hadronic interactions.

The MINIMAX Collaboration has analyzed \( 1.5 \times 10^6 \) events at \( E_{cm} = 1.8 \) TeV corresponding to a lab energy of 2 PeV. A set of observables \( r_i \) with

\[
r_i = \frac{(1-f)(f(1-f)^i)}{f((1-f)^{i+1})}
\]

has been defined which are rather insensitive to experimental errors. They all are \( \equiv 1 \) for binomial fluctuations and \( 1/(i+1) \) for pure DCC events. Tab. 1 shows the result in comparison with PYTHIA calculations [11] including 5% and 10% DCC events. This comparison shows no evidence for DCC in the data, i.e. at the level \( \leq 1\% \). The results rather suggest \( r_i \geq 1 \) [15].

Since this result is obtained from \( p-\bar{p} \) collisions, it does not exclude large fluctuations in \( f \) for nucleus-induced collisions. A recent analysis of 158 GeV/n Pb-Pb collisions by the WA98 Collaboration, however, sets only upper limits of the DCC content in their data [2].

<table>
<thead>
<tr>
<th>Obs.</th>
<th>Data</th>
<th>Monte Carlo 5% DCC</th>
<th>10% DCC</th>
<th>DCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r_1 )</td>
<td>1.0228±0.0035</td>
<td>0.97±0.02</td>
<td>0.95±0.02</td>
<td>0.5</td>
</tr>
<tr>
<td>( r_2 )</td>
<td>1.0320±0.0097</td>
<td>0.93±0.05</td>
<td>0.89±0.04</td>
<td>0.333</td>
</tr>
<tr>
<td>( r_3 )</td>
<td>1.0563±0.0251</td>
<td>0.95±0.10</td>
<td>0.89±0.08</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Further analyses of MINIMAX data are in progress. Soon, better limits on DCC, pseudorapidity distributions for charged and neutral pions, and data on \( K^0 \) and \( \Lambda^0 \) production will be available.

2.4 Future Accelerator Experiments

With the FELIX experiment a full acceptance detector is proposed at the Large Hadron Collider LHC [27]. It aims for full coverage in \( \eta \) and \( \phi \) for charged and neutral particles and will reuse the magnets of ALEPH, UA1, D0, RHIC DX, and UNK in different rapidity ranges. A schematic view is shown in Fig. 4. With this set of magnets the experiment will have a reasonably uniform \( p \) and \( p_\perp \) resolution over the whole acceptance. FELIX will be able to investigate particle production beyond \( \eta = 7 \). It is well suited for small angle physics, hard and soft QCD phenomena in \( p-p, p-A \) and \( A-A \) collisions, and for search for cosmic-ray anomalies.
With the start of operation of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven in spring 1999, another facility will become operational that can deliver new insights into the physics of heavy ion collisions. Experiments will search especially for signatures of the onset of new physics in central Au collisions at 200 GeV/n, e.g. the phase transition to quark gluon plasma [49].

3 Interaction and EAS Models

Presently there are several Monte Carlo programs being used for the full simulation of EAS development in the atmosphere. The most common ones and the models used for high-energy hadronic interaction are shortly described in the following sections.

3.1 Available Codes

CORSIKA [17, 61, 44] is a multi-purpose shower simulation program of air shower development. It contains the hadronic interaction models VENUS [79], QGSJET [55], DPMJET [71], SIBYLL [31, 28], and HDPM [16, 17] at high energies and GHEISHA [30] and EGS4 [67] for low-energy hadronic and electromagnetic interactions, respectively. VENUS, QGSJET, and DPMJET base on the Gribov-Regge theory of multi-Pomeron exchange, which has been used successfully over decades to describe elastic and inelastic scattering of hadrons. Especially nucleus-nucleus collisions and diffraction are treated in great detail in these models. SIBYLL is a minijet model that describes the rise of the cross-section with energy by increasing the pairwise minijet production. HDPM uses parametrizations along the collider data for \( p\bar{p} \) collisions. The latter two models apply the Glauber theory for hadron-nucleus collisions and treat projectile nuclei as a superposition of free nucleons. With the appropriate interaction models CORSIKA can simulate air showers up to \( 10^{21} \) eV. A thinning algorithm according to Hillas keeps computing time and disk space to a manageable level. CORSIKA versions exist for Cherenkov light production, horizontal showers, neutrino generation and several other special purposes. All parts of CORSIKA are described in detail and are available to the cosmic-ray community.

HEMAS [32, 9] was originally developed for the MACRO and NUSEX experiments on the basis of the SHOWERSIM program [82] with extensions to energies of around \( 10^{17} \) eV. These experiments only register high-energy muons underground and, therefore, only the simulation of the high-energy part of the air shower and the lepton production had been emphasized. Detailed transport of TeV muons through rock [64] was implemented and nuclear reactions were treated under the superposition assumption. In the most recent version of HEMAS the hadronic event generator was replaced by DPMJET including an elaborate algorithm for nuclear fragmentation [29]. In addition, the low-energy part of the cascade development was improved for the use with the EAS-TOP experiment measuring the low-energy shower particles.

MOCCA [45, 46] is one of the first EAS programs and was developed by M. Hillas in the 1980s. Its original hadronic interaction model is the so-called splitting algorithm which produces secondaries following a very simple qualitative prescription with 2 free parameters. To overcome the limitations of this simple event generator, the more elaborate SIBYLL code has been implemented. MOCCA can only deal with protons, neutrons, pions, kaons, electrons, and photons, neglecting all excited and short-lived states that can be produced in high-energy interactions. Due to a statistical thinning algorithm, MOCCA is able to simulate showers up to highest energies. Mean values are reproduced well, but the fluctuations of shower quantities are grossly overestimated when thinning too much. MOCCA optionally performs a simple simulation of the reactions of the shower particles with the detector materials. Using other
EAS programs this part of the simulation has to be done in a separate step, e.g. with the well accepted detector Monte Carlo program GEANT [36].

**AIRES** [72] presently is a translation of MOCCA into standard Fortran with much of the code being restructured and documented. The detector simulation part has been omitted. It is envisaged for the future to extend the program by other interaction models and unstable particles, and to improve the algorithms for particle transport, decays and shower development.

There are some more programs in use in the air shower community. But these are either special purpose programs or private versions of one experiment, the physics input of which is not published in detail and which are not generally available.

**GENAS** [57] is constructed for high-speed calculation of EAS in the $10^{20}$ eV range. Electromagnetic subcascades are computed by the **COSMOS** program [56]. GENAS/COSMOS is used to interpret the AGASA data. It is not a full Monte Carlo program, but uses parametrizations for electron and photon numbers as a function of core distance for different atmospheric depths. Only 6 groups of projectiles are distinguished, from proton & He, light heavy ($\langle A \rangle = 8$), medium heavy ($\langle A \rangle = 14$), heavy ($\langle A \rangle = 25$), very heavy ($\langle A \rangle = 35$) to iron. Secondary muons and hadrons are neglected.

**MC0** and **MJE** are used for the interpretation of results obtained by the emulsion chamber experiments at Pamir (see e.g. Refs. [14, 70, 85]). They are based on the Quark Gluon String model with minijet production. However, their capabilities and limitations are not well described in literature.

Hadronic interaction models exist which are used for high-energy accelerator experiments. **PYTHIA** [11, 73] models hadronic interactions with high momentum transfer according to QCD, takes into account resonance formation as well as gluon radiation from quarks and contains the fragmentation of colour strings into colour neutral hadrons. It also contains the soft (minimum bias) processes, which are important for air showers, but cannot handle primary mesons or nucleus-nucleus collisions. **FRITIOF** [68, 5] is able to simulate hadron-nucleus and nucleus-nucleus collisions on the basis of the classical string theory. The results for hadron interactions are similar to those of Gribov-Regge models. For the treatment of nucleus-nucleus collisions FRITIOF adopts the superposition model. A combination of FRITIOF and PYTHIA could, in principle, be used to simulate EAS.

### 3.2 Model Comparisons

The major systematic uncertainties in EAS analysis arise from the lack of knowledge of the total cross-sections and the details of particle production for nuclear and hadronic reactions at high energies with small momentum transfer. The experimental findings at proton colliders have to be extrapolated over many orders of magnitude to CR energies, small emission angles and nuclear projectiles and targets.

To estimate the systematic errors, a detailed comparison of hadronic interaction models inside the frame of the CORSIKA program has been performed [62]. The models involved were **VENUS**, **QGSJET**, **DPMJET**, **SIBYLL** and **HDPM**. Their basic properties are summarized in Tab. 2.

#### 3.2.1 Cross-Sections

The first quantities compared are the inelastic p-air cross-sections $\sigma_{p\rightarrow\text{air}}^{\text{inel}}$. All models except for SIBYLL calculate $\sigma_{p\rightarrow\text{air}}^{\text{inel}}$ from the experimentally well determined $\sigma_{p\rightarrow p}^{\text{inel}}$ by assuming a distribution of the nucleons in the air nuclei. Therefore, all these models agree reasonably well with each other (and the collider data) and start to diverge only at energies where no measurements exist anymore. The calculation of $\sigma_{p\rightarrow\text{air}}^{\text{inel}}$, however, leads to rather different results.
as shown in Fig. 5, where the cross-sections are plotted together with experimental data from cosmic-ray experiments. HDPM predicts the smallest cross-section exhibiting the flattest rise with energy. The Gribov-Regge type models show a comparable rise but differ by about 50 to 100 mb. Generally, they are below the experimental points at high energies.

SIBYLL has adopted a parametrization for $\sigma_{\overline{p}-p}^{\text{inel}}$ which at $p_{\text{lab}} < 10^6 \text{ GeV/c}$ exhibits the flattest rise with values clearly below the experimental results. At $p_{\text{lab}} > 10^6 \text{ GeV/c}$ it rises steeply and surpasses all other models. As a consequence, $\sigma_{\text{inel}}^{p-\text{air}}$ in SIBYLL also rises more steeply than in any other model, fitting best the data points in Fig. 5. The MOCCA cross-section grows even faster than the SIBYLL one with up to 100 mb higher values at $p_{\text{lab}} \approx 10^8 \text{ GeV/c}$.

In the most recent version of DPMJET (II.4, not yet available in CORSIKA) $\sigma_{\text{inel}}^{p-\text{air}}$ has been corrected downwards by 25 mb and now agrees nicely with the cross-sections of VENUS and QGSJET at low energies. A new analysis of the EAS-TOP Collaboration determined the p-air cross-section at $p_{\text{lab}} \approx 2 \times 10^6 \text{ GeV/c}$ to be $\sigma_{\text{inel}}^{p-\text{air}} = 344 \pm 12 \text{ mb}$ [3], in contrast to the high values of Ref. [34] and in reasonable agreement with the predictions of the Gribov-Regge models.

The spread between the models amounts to about 100 mb or 25% in the region of the knee of the all-particle spectrum. Since the inelastic cross-section determines the mean free path of a particle in the atmosphere, it influences directly the longitudinal shower development. A larger cross-section causes shorter showers and, consequently, fewer particles at ground level. The differences in $\sigma_{\text{inel}}^{p-\text{air}}$ for comparable assumptions of $\sigma_{\text{inel}}^{\overline{p}-p}$ originate partially from different applications of the Glauber theory and from varying assumptions regarding the form of the target nuclei. The discrepancies between the models are rather big, taking into consideration that all authors use basically the same approach to calculate the cross-sections. By agreement on the best method of calculation, a big part of the discrepancies should vanish.

### 3.2.2 Particle Production

The production of secondaries in hadronic interactions also differs between models. A variety of quantities has been examined, the results are described in Refs. [60, 62]. The quantity with the largest impact on air shower development is the inelasticity, i.e. the fraction of the energy of a projectile that is used for production of secondary particles. Again, a variation in this quantity directly implies a modification of the longitudinal shower development. The inelasticity does not vary much with energy, but differences between the models amount to 20 to 30%.

The effects of inelasticity and cross-sections are basically independent and may cancel out or add up. For DPMJET with the largest inelasticity and the largest cross-sections the

<table>
<thead>
<tr>
<th>Tab. 2: Basic features of the interaction models used in CORSIKA.</th>
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<tbody>
<tr>
<td><strong>Grivob-Regge</strong></td>
</tr>
<tr>
<td>Minijets</td>
</tr>
<tr>
<td>Sec. Interactions</td>
</tr>
<tr>
<td>N-N Interaction</td>
</tr>
<tr>
<td>Max. Energy (GeV)</td>
</tr>
<tr>
<td>Memory (Mbyte)</td>
</tr>
<tr>
<td>CPU Time$^1$ (min)</td>
</tr>
</tbody>
</table>

$^1$ 500 p showers at $10^{15} \text{ eV}, E_\mu, E_h > 0.3 \text{ GeV}, 110 \text{ m a.s.l.}, \text{ NKG option, on DEC-AXP 3600 (175 MHz)}$
showers are very short, while they are longest for HDPM with the smallest inelasticity and the smallest cross-sections. This leads to differences between the predictions of the electron or muon number in a $10^{15}$ eV EAS at sea level of about a factor of 2, or, conversely, to a corresponding systematic error in the shower energy when it is determined from the particle number at ground level only [62].

Similar comparisons of the MOCCA and SIBYLL interaction generator inside AIRES and of DPMJET and the older interaction model inside HEMAS are in preparation and will soon shed additional light on the systematics of hadronic interaction models.

3.2.3 Other Comparisons

Besides a comparison of different interaction models in the same program frame, comparisons of different frames with identical hadronic interaction models are of interest. They reveal the systematics of the electromagnetic interactions, particle transport, decays, treatment of low-energy particles and the whole philosophy of the simulation. Such tests are in progress by comparing CORSIKA with SIBYLL and MOCCA or AIRES with SIBYLL, CORSIKA with DPMJET and HEMAS with DPMJET, and CORSIKA with QGSJET and MC0. The CORSIKA/SIBYLL showers, e.g., develop about 10-20 g/cm$^2$ higher in the atmosphere than the corresponding MOCCA/SIBYLL showers.

3.3 Improvements

The model comparisons so far have brought the systematics of EAS analysis to the attention of the community and to the authors of the interaction models. It has triggered already a series of improvements. There is a new DPMJET (version II.4) available with modified cross-sections and an improved treatment of nuclear fragmentation. The authors of SIBYLL began to revise their code and the cross-sections used. The authors of VENUS and QGSJET started a collaboration to unify their codes by combining the best parts of each program and forming a model to the best of the present knowledge [69]. The new VENUS/QGSJET should be available by the end of 1997. The HDPM model obtained an improved $p_{\perp}$ generator taking into account the correlations of $\langle p_{\perp} \rangle$ and the central rapidity density and a better treatment of nuclear fragmentation by means of an abrasion/evaporation algorithm [19, 20].

3.4 Further Simulation Activities

A series of other new activities around the shower simulation were reported recently.

Gaisser, Lipari and Stanev [35] presented a new, fast, 1-dim. shower calculation to obtain the longitudinal profiles of $10^{20}$ eV showers by using precalculated lower-energy pion-induced showers and a bootstrap method. It allows to examine quickly the effects of details of the interaction model as has been demonstrated in Fig. 1 of Ref. [35].

Vassiliev et al. [76] presented a new algorithm for a faster and better calculation of the Cherenkov light production from electromagnetic subshowers of EAS. The algorithm, being specialized for only one energy range of interest, uses extensively lookup tables and a thinning technique for the Cherenkov photons.

Konopelko and Plyasheshnikov [63] advocate a semianalytical Monte Carlo technique (SAMC) for speeding up high-energy shower calculations. In contrast to most other approaches they solve the adjoint cascade equations for the high-energy part of the shower analytically and perform a full Monte Carlo simulation for the low energies. The authors claim that with this approach the fluctuations of shower quantities can be accounted for properly while this is not the case for other thinning techniques or hybrid Monte Carlo programs.
Capdevielle et al. [20] elaborated a fast method for simulation of the electromagnetic part and the fluorescence light of highest-energy air showers.

### 3.5 Impact on EAS Analyses

The impact of the above-quoted systematic discrepancies between different EAS models can be demonstrated for the results on CR composition in the energy range from $10^{17}$ to $10^{19}$ eV obtained by the Fly’s Eye and the Akeno experiments.

The Fly’s Eye detector consists of many photomultipliers, each observing a small segment of the night sky. The charged particles in a shower induce nitrogen fluorescence in the air which can be registered over large distances for primary energies above $10^{17}$ eV as a track across several photomultiplier pixels. From the signals in each photomultiplier the light curve is reconstructed. Since the fluorescence light is mainly produced by the large number of low-energy electrons, the light curve traces closely the energy deposition in the atmosphere, and, hence, the longitudinal shower development in a calorimetric way. The integral over the light curve is a good measure of primary energy and the height of the maximum of the shower development relates to the mass of the primary particles. In 1993, the Fly’s Eye Collaboration published the average depth of shower maximum as a function of energy and found a change with energy. The elongation rate $dX_{\text{max}}/dE$ was larger than the predictions by their KNP model for pure compositions of either protons or iron nuclei [12, 33]. On the basis of these simulations it was concluded that the composition changes from almost pure Fe at $E \approx 10^{17}$ eV to nearly pure p at $E \approx 10^{19}$ eV.

However, the other experiment which observes EAS in this energy range could not confirm the Fly’s Eye result. The AGASA experiment at Akeno is a 100 km$^2$ scintillator array with 111 electron detectors and 27 muon detectors for $E_\mu > 0.5$ GeV. The density of charged particles $\rho_{600}$ at a core distance of 600 m was used as energy estimator and the muon density at the same distance served as mass indicator. In the AGASA data a change of composition should have led to a change in the ratio of the observed muon density to the one expected for constant composition. No such change was observed. The analysis, however, was based on calculations with the GENAS/COSMOS model. This claim was affirmed by a new analysis [43] of a dataset with 7.5 times the statistics of the old experiment. The mass change is $< \pm 5$ in the energy range from $E = 3 \times 10^{17}$ to $10^{19}$ eV. Their result stays basically unchanged when employing MOCCA/SIBYLL for the analysis [43].

Are the Fly’s Eye and the AGASA results really contradicting each other? It was soon emphasized that the different conclusions just reflect the differences in the Monte Carlo programs used.

Kalmykov et al. [54] compared the Fly’s Eye data with data from the Yakutsk array [24] and with calculations using their QGSJET program (see Fig. 6). They found good agreement between the experiments and with the simulations when assuming the $\sum$ composition of light : medium : heavy $\approx 0.55 : 0.22 : 0.23$ at $E < 3 \times 10^{15}$ eV with a very smooth change towards heavier nuclei leading to $0.23 : 0.22 : 0.55$ at $E = 10^{17}$ eV.

Gaisser et al. [35] showed that SIBYLL gives a somewhat larger elongation rate than the KNP model and, therefore, leads to a modified conclusion concerning the change of mass composition.

On the other hand, Dawson et al. [22] compared data of the A1 stage of the AGASA array with MOCCA/SIBYLL simulations and found a similar change of composition as described in the original Fly’s Eye publication (see Fig. 7). The calculations were performed for a muon energy threshold of 1 GeV, corresponding to the threshold of the muon detectors. In contrast, the analysis described in [43] used simulations with a muon threshold of 0.5 GeV and corrected for the mismatch. This may be the reason for the apparent discrepancy of the results of Refs.
As a conclusion, the situation in EAS physics is presently like the one sketched in Fig. 8: better use the same yardstick (i.e. Monte Carlo program) to get consistent results in different experiments, and use a well calibrated, reliable yardstick to obtain the correct result. In other words, the interpretation of EAS data strongly depends on the air shower model used, as long as the models differ the way they presently do.

For progress in the interpretation of EAS measurements, we feel that it is vitally important to make a common effort towards a reference simulation program that contains the best and most detailed treatment of all physical processes relevant to EAS and that is used and tested by groups working in all parts of cosmic-ray physics without adapting the physics parameters for each experiment in a different way. There is a very successful example of such an activity. The CERN detector simulation package GEANT [36] has evolved over the past decade to one of the most powerful and efficient tools of high-energy physics experiments. By the contribution of many users and experiments, the algorithms for each aspect of the simulation have been refined continuously and have acquired a quality which is beyond the reach of a single person or a small group. It is nowadays the de facto standard for the simulation of the detailed response of detectors in complex setups to the incidence of all kinds of radiation or relativistic particles.

Such a reference should also serve to estimate the performance of special purpose programs that are optimized for particular aspects of CR physics, such as fast calculations of highest energy showers, TeV muons, Cherenkov light production, and so on.

4 Air Shower Arrays

4.1 Multiparameter Measurements

Air shower analyses are based on the comparison of experimental data with MC simulations. To be able to perform such a comparison, a spectral form, an energy-dependent mass composition and parameters of the high-energy interactions have to be assumed. Therefore, a discrepancy between MC and data can have many sources and, on the other hand, an agreement does not necessarily mean that all the assumptions are right. Especially when registering only one observable (e.g. \( N_e \)) several parameter settings may exist that can reproduce the observation. Fluctuations in the observable are then directly projected onto uncertainties in primary energy or mass.

When measuring several quantities it is possible to recognize fluctuations. A big part of the shower fluctuations originates from the first hadronic interaction. If, by chance, in this interaction more than average \( \pi^0 \)'s are produced, more energy is transferred to the electromagnetic and less to the hadronic and muonic component. An energy estimate based on the electromagnetic energy only, therefore, will overestimate the primary energy. Taking all components into account, one realizes that the deficiency in one component is partially compensated by an excess in another component and, consequently, obtains a better energy estimate. Similar arguments hold for the varying height of the first interaction.

With multiple observables in addition correlations between shower variables can be investigated which allow to test model assumptions more stringently and to disentangle influences of different sources on the observables.

In recent years, the need of multiparameter measurements was recognized and many of the air shower experiments were upgraded or designed to be able to measure simultaneously as many shower variables as possible. The HEGRA experiment has been extended with the AIROBICC Cherenkov counter array and with muon detectors. CASA-MIA was completed by the DICE Cherenkov telescopes and the BLANCA Cherenkov light detectors. The EAS-TOP
Collaboration enhances the shower information by the registration of high-energy muons seen in the underground detectors in the Gran Sasso tunnel. KASCADE measures the electromagnetic, muonic, and hadronic component with high resolution and high dynamic range.

Many results on spectra and composition of cosmic rays have been presented at this conference, most of them, however, in the session OG 6. Therefore, they are summarized in the rapporteur article by A.A. Watson [77] in this volume.

4.2 EAS-TOP

The EAS-TOP experiment at the Gran Sasso in Italy measures air showers at 2000 m a.s.l. with a $10^5$ m$^2$ scintillator array (35 stations, 10 m$^2$ each) and a 144 m$^2$ muon/hadron detector, consisting of 9 layers of tracking and proportional chambers in an absorber of 6 $\lambda_I$ thickness. With the EAS-TOP detectors the electron number and the number of muons with $E_\mu > 1$ GeV can be determined. Below the array the underground experiments MACRO and LVD are run and coincidences with the array are registered. The rock shielding is equivalent to 3400 m of water absorbing the electromagnetic, hadronic and most of the muonic part of EAS. Only muons with energies exceeding 1.3 TeV can reach the underground detectors. Coincident events allow to investigate additional parameters of an air shower in correlation with the ones measured by the array and the muon/hadron detector. Results of coincident measurements of EAS-TOP and LVD were reported in Ref. [26]. LVD is a liquid-scintillator detector with 78 m$^2$ area for a good $dE/dx$ measurement combined with limited streamer tubes for good tracking. Based on MC calculations, very stringent cuts in $N_e$ (measured by EAS-TOP) and the high-energy muon number $N_\mu$ TeV (measured by LVD) were defined to select p and Fe-enriched samples with a low efficiency but a high purity. For the resulting event samples the number of low-energy muons as measured in the array $N_\mu$ GeV were investigated. The results in this independent variable agree nicely with the Monte Carlo expectations for p and Fe-induced showers as shown in Fig. 9. This is a test of the EAS models involved and the agreement indicates a good description for the observables used and their correlation. Such multiparameter measurements allow consistency checks and stringent tests of the EAS models which are not possible with only one measured quantity.

As already mentioned a new measurement of the inelastic p-air cross-section was presented by the EAS-TOP Collaboration [3]. It was evaluated by the analysis of the rate of showers with the same electron and muon number for different zenith angles and amounts to $\sigma_{\text{inel}}^{\text{p-air}} = 344 \pm 12$ mb at $p_{\text{lab}} \approx 2 \times 10^6$ GeV/c [3]. This value is about 100 mb or 25% lower than previous measurements [50, 7, 34]. What could be the reason for this large discrepancy? While the raw data of AKENO and EAS-TOP do not differ much, the disagreement appears after applying a correction factor which accounts for the bias in the attenuation length due to the analysis procedure. In case of EAS-TOP the correction is energy-dependent from 1.1 to 1.4. It was obtained by a full MC simulation of the shower development, the detector response and the reconstruction procedure. The AKENO Collaboration applies a constant correction of 1.5. The difference in the correction factor has about the size of the discrepancy. This comparison suggests a strong dependence of the result on details of the analysis procedure. The difference of 25% between EAS-TOP and AKENO may serve as an estimation of the systematic error.

With its muon/hadron detector the EAS-TOP Collaboration has measured the flux of single hadrons at 2200 m a.s.l. and found

$$I(E_h) = (1.89 \pm 0.21) \times 10^7 \cdot (E/\text{TeV})^{-(2.67\pm0.14)}/(\text{m}^2\text{ sr}\text{ GeV})$$

The data are shown in Fig. 10. The flux of TeV hadrons is about 5 times higher than the one measured near sea level [65]. From the comparison of the two results an attenuation length of
Λ = 115.9 g/cm² is deduced. Under the assumption that a single hadron at ground level is a particle closely related to a primary proton and survived the interactions as leading particle the attenuation length Λ is directly related to the interaction length λ_{int} and the inelasticity η of the interaction by the form Λ = λ_{int}/(1 - (1 - η^γ)) [10]. γ is the slope of the primary energy spectrum. Using this relation, the inelastic proton air cross-section of σ_{p-air}^{inel} ≈ 290 mb at E = 1 TeV, and the above-quoted value of Λ, an inelasticity of η ≈ 0.47 is obtained. The quoted error of this estimate is ±0.07, but the systematic uncertainties of the assumptions and the formula used are probably larger than that. A MC study could reveal how well these simple relations hold in a realistic environment with fluctuations and imperfect detection systems.

4.3 KASCADE

Measuring different components in an EAS bears the problem of each detector designed for one shower component being sensitive to the others as well, to some extent. If the components are to be identified separately, e.g. in a setup with e/γ detectors above and μ detectors below an absorber plate, the energy depositions in the e/γ detectors need to be corrected for penetrating muons and hadrons and the signals of the μ detectors for the electromagnetic and hadronic punch-through. The correction, however, depends in general on the type and energy of the primary particle as well as on the zenith angle and the distance of a detector to the shower axis. The contributions of the various components to the energy deposit were investigated for the array electron and muon detectors of the KASCADE experiment [78]. A set of appropriate correction functions was evaluated in an iterative way (see Figs. 1 & 2 in Ref. [78]) and finally meaningful values for the electron and muon numbers N_e and N_μ were obtained. Several analyses on the composition and energy spectra rely on N_e and N_μ determined this way.

The KASCADE experiment finds a pronounced knee in the electron and the muon size spectra [38]. The slopes of the electron size spectrum are −2.45 ± 0.01 ± 0.05 below and −2.94 ± 0.02 ± 0.1 above the knee and for the muon size spectrum the corresponding numbers are about -3.0 and -3.4. The position of the knee varies with zenith angle [38] in contradiction to findings of the Tien Shan Collaboration [53] which sees the knee for all zenith angles at the same N_e. The KASCADE findings are in agreement with the EAS-TOP results as presented at the last European Cosmic Ray Conference [25]. With improved statistics a two-dimensional analysis will become feasible.

The unique part of KASCADE is a large hadron calorimeter. Measuring the hadron component in addition to the muonic and electromagnetic components allows multiparameter analyses with the use of correlations between single variables and a sensitive test of the EAS models.

It has been noted earlier [60] that the SIBYLL model predicts fewer muons for high-energy air showers as compared to other models. This leads to a strong discrepancy between data and simulation, e.g. in the energy spectra of hadrons as shown in Fig. 11 [47]. While the data points lie between VENUS predictions for p and Fe-induced showers, leading to a composition estimate between p and Fe, they lie outside the range of SIBYLL predictions. Thus, with SIBYLL one would predict a composition much heavier than iron even below the knee. Since the number of muons was used to classify the showers, higher energies are needed with SIBYLL to populate the same bin and consequently the predictions for hadrons are higher, too. However, when examining a quantity which is independent of the muon number, SIBYLL performs much better as shown in Fig. 12. It is apparent that the results of the analysis depend strongly on the model. In the case discussed here, the muon production in SIBYLL seems to underestimate muon production, the hadronic part, on the other hand, looks reasonable. This result is amazing, since muons originate mainly from decaying charged pions, i.e. from the hadronic component. The example illustrates the power of multivariate measurements including
the hadronic part of EAS. Several hadronic observables have been investigated and compared to various hadronic interaction models [47, 48]. Overall, CORSIKA calculations using QGSJET and VENUS reproduce the experimental data best.

The KASCADE Collaboration presented four, still independent, analyses of the composition from their data, comparing it to CORSIKA simulations with VENUS and QGSJET. One analysis uses the $N_e/N_\mu$ ratio as mass indicator [78], in another the structure of the hadronic shower core is examined [47, 48], and in one multivariate analysis techniques are used, combining several of the array observables available on an event-by-event basis [21]. The results are shown in Fig. 13. Though the results are still preliminary and some inconsistencies have to be understood, all four analyses show qualitatively a similar behaviour. There is a basically constant average mass for growing energy up to about the knee region where a rise towards heavier masses sets in.

Another interesting result from the hadron calorimeter of the KASCADE experiment was presented in Ref. [66]. The longitudinal shower development of single hadrons has been examined for hadrons well above the energies accessible by man-made accelerators (see Fig. 14). Thus, cosmic-ray hadrons allow a test of the interaction codes used for detector simulations in high-energy physics. In general, GEANT simulations with the FLUKA interaction model describe the data quite well up to energies of 10 TeV. In addition, for energies ≥ 5 TeV, the shower attenuation is shown as measured by Yakovlev et al. [83] at Tien Shan. The authors see a flattening of the attenuation with rising energy which they attribute to the existence of a new long flying component. The comparison with the KASCADE and the GEANT shower curves, however, shows that there is reasonable agreement between them at depths between 2 and 5 $\lambda_I$, i.e., in the range which was covered by the Tien Shan detector. A small decrease of attenuation in this range of depth is predicted by GEANT without any new physics, due to the shift of the shower maximum with rising energy to larger depths. Consequently, no indication of new physics from hadronic shower curves can be established, at least up to 10 TeV, by the KASCADE experiment. In the near future the statistics of isolated high-energy hadrons in the KASCADE calorimeter will increase strongly, leading to shower profiles for energies up to 50 TeV. Further information on KASCADE results can be found in Ref. [59] in this volume.

5 Emulsion Chamber Experiments

A traditional method to investigate cosmic rays and high-energy hadronic interactions is by means of emulsion chambers. A stack of absorbers and sheets of track detectors is exposed to cosmic radiation. It is irradiated for typically a year or two before the track detectors are processed. Thus, the definition of an event as an ensemble of tracks is purely based on geometry. Emulsion chambers have a superb spatial resolution ($\approx \mu m$), however, the x-ray films have a rather high threshold for photons in the TeV region and hadrons are not seen at all. Thus, the experiments suffer from the large fluctuations in the fraction of $\pi^0$s produced.

Emulsion chambers are mostly operated at mountain altitudes or above the atmosphere and aim for secondaries of a single interaction either in the atmosphere above the chamber or in an absorber plate.

Typical setups have 2 storeys, the upper one for detection of photons from the atmosphere and the lower one for detection of photons produced in the absorber material of the upper layer.

Fig. 15 shows a schematic view of a cosmic-ray event as measured by an emulsion setup and a typical pattern observable in one emulsion sheet. The principle of measurement with emulsion chambers was described recently in Ref. [58].

Energy determination of the photons is based on the optical density of the film. The
average darkness in a radius of 50 µm around a spot is related to the energy deposit: The larger and the darker the spot, the higher is the energy deposit. The spot size is determined by the contour line with optical density = 0.5. If the area of the spot is < 4 mm², the track is attributed to a single photon, if the area is > 4 mm², it is called a halo. An example of a halo event is shown in Fig. 16. The optical densities in different layers are combined to an estimate of the photon energy. Since TeV photons are not available at accelerators, the energy calibration cannot be verified experimentally. Therefore, the response of X-ray films to γ families has been simulated recently using the CORSIKA and GEANT program packages [42]. The resulting relation between average optical density and photon energy is shown in Fig. 17 for different zenith angles. The shaded line indicates the calibration function used by the PAMIR Collaboration for experimental data.

The reconstruction of the energy $E_\gamma$ of the γ-family is a convolution of the reconstruction quality for single photons and the energy and angular distribution of the photons in an event. On average the reconstruction using the PAMIR calibration reproduces the “true” MC energy bias free, the fluctuation extends up to 50% as shown in Fig. 5 of Ref. [42].

5.1 Aligned Events

The PAMIR Collaboration observed a number of events in which the single particles of a family or groups of particles form a straight line [74]. An example of such an event is shown in upper part of Fig. 18 [14].

A strong alignment of the energy deposition was also found in the most energetic event registered in emulsion chambers by the CONCORDE Collaboration [18]. The emulsion chambers were exposed at flight altitude of the CONCORDE aircraft which is 17 km corresponding to an overburden of 100 g/cm². At those heights it is most likely that the secondaries observed in an event originate from a single collision in the air above the plane. The event is sketched in the lower part of Fig. 18. In total 1600 TeV have been observed in this event giving a primary energy of > $10^{17}$ eV. 90% of the energy is contained in 4 clusters that are aligned. The 4 most energetic individual photons (300, 105, 75, and 53 TeV) lie perfectly on a straight line.

Events of this type are expected to some extent. In $p\bar{p}$ collisions at CERN or Fermilab events with high $p_\perp$ jets are measured and well understood in the framework of QCD. In the rest frame of one of the collision partners such an event would produce automatically three coplanar jets entailing three aligned groups of spots in a detector system. More than 3 clusters may be produced from initial states with high angular momentum. String fragmentation tends to produce particles in a plane, too. Several other ideas have been put forward to explain such events qualitatively. Hence, the claim of an unusual phenomenon requires a statistical analysis taking all these possible mechanisms into account.

The PAMIR group has performed an analysis of the planarity of their families using the two variables

$$\lambda_N = \frac{\sum_{i\neq j\neq k} \cos 2\phi_{i,j}^k}{N(N-1)(N-2)} \quad \text{and} \quad \alpha = \frac{\sum_{i\neq j} \cos 2\varepsilon_{i,j}}{N(N-1)}.$$ 

$\phi_{i,j}^k$ is the angle between the vector $(i,j)$ and the vector $(i,k)$ and $\varepsilon_{i,j}$ is the angle between the vector $(i,c)$ and the vector $(j,c)$ where $c$ denotes the center of gravity of the gamma family. Both variables are 0 for isotropic events and = 1 for perfectly aligned events.

While Monte Carlo simulations using the programs MC0 and MJE reproduce the data at $\sum E_\gamma < 400$ TeV, there is an excess of aligned events at a level of 2σ for higher energies [14, 85]. The excess of alignment is present for events with three, four or five distinct particle groups. By combination of several distributions, a chance probability of such a result is estimated to be < $10^{-5}$ [74].
In the case of the CONCORDE data, no such comparison has been performed yet. The published event is the most energetic one and it is aligned. Thus, it is suggestive that alignment may be a rather common feature at high energies.

To further confirm the statement that alignment is due to new physics with a threshold at about 400 TeV, it should be checked whether an alternative interaction model, e.g. a high $p_t$ event generator from collider physics, or some of the mechanisms proposed in the literature can quantitatively explain the phenomenon. In addition, a thorough statistical analysis of fluctuations and methodical or selection effects would be necessary in order to prove whether the unusual events originate from a tail of a distribution or belong to a separate population.

Due to the complicated handling and off-line processing of emulsions and X-ray films and due to the very high-energy threshold of the films, an alternative detection technique would be desirable to clarify the experimental situation. Recent progress in detectors using scintillating fibers and capillaries or in time-projection chambers using liquid active materials have made a $\mu$m resolution feasible.

### 5.2 Halo Events

Altogether the PAMIR Collaboration found 39 events with halos for $\sum E_\gamma > 500$ TeV (see Fig. 16). These events were compared to MC simulations of showers induced by single high-energy neutral pions (300-5000 TeV) and nuclear-electromagnetic cascades ($E_0 > 10$ PeV) [75]. The Monte Carlo code used was MQ, which describes the main features of $\gamma$-hadron families. This code is based on the QGS model, but its details are unpublished. The lateral distribution of darkness in the resulting spots for data and simulations were compared and it is concluded that the large areas seen in experimental data cannot be explained by simulations of high-energy $\pi^0$s or shower cores. However, it is crucial that the quoted program is able to reproduce the response of the detector to a superposition of very many low-energy subcascades as they occur in the core of a hadronic shower as well.

### 5.3 Centauro Events

Another exotic phenomenon reported repeatedly in the past are the Centauro events. They were registered at Chacaltaya (Bolivia, 5200 m a.s.l.) with a two-storey setup of emulsion chambers shown in Fig. 19. Both layers register only photons of TeV energies. The upper layer is directly sensitive to photons whereas spots in the lower layer are interpreted as secondaries created from hadrons in the upper or the target layer and, thus, trace the number of hadrons in the event. For normal reactions in the atmosphere the expectation is

\[
\frac{N_\gamma/2}{N_h} \approx \frac{N_{\pi^0}}{N_{\pi^+\pi^-}} \approx \frac{1}{2}.
\]

Centauro events are those showing much fewer photons than expected ($Q_h = \sum E_h/(\sum E_h + \sum E_\gamma) \approx 1$), Anti-Centauro events are those with much more photons ($Q_h \approx 0$). The events are usually displayed in the $N_h$-$Q_h$ plane as shown in Fig. 20. A new Centauro candidate [8] is plotted with a total energy of 57 TeV and $N_h = 13$, $Q_h = 1.0$, i.e. with only hadrons and not a single photon above the threshold. Fig. 20 also shows the distributions of approximately the same number of simulated events as the data sample, initiated by various primary nuclei. They exhibit a broad distribution and scatter from $Q_h = 0$ to 1 due to fluctuations of the $N_{\pi^0}/N_{\pi^+\pi^-}$ ratio. When assuming binomial fluctuations in the number of charged and neutral pions one expects $8.7 \pm 1.7 \pi^\pm$ in an event with 13 pions in total. The chance probability for no $\pi^0$ and 13 $\pi^\pm$ would then be $5 \times 10^{-3}$. From the plot containing about 4200 simulated events and none in the region near the measured event the chance probability can be estimated to be $< 2 \times 10^{-4}$,
depending on the interaction generator. Indeed, several authors claim to be able to reproduce qualitatively Centauro-type events with suitable interaction models [6, 40]. Whether the new event or the whole class of Centauros are unexplainable by known physics can only be decided after a careful statistical study of the complete event set, including the bias due to possible selection effects. Such an analysis is very difficult and has not yet been performed. As for the aligned events and halo events, the data are suggestive but the results are not convincing yet. A dedicated search for anomalies in the fluctuations of the number of charged pions in $p-\bar{p}$ collisions has been performed with the MINIMAX experiment as mentioned in Sec. 2.3. No indications of unusual fluctuations have been found so far.

6 Conclusions

The main progress over the past years in the field of high-energy interactions and air shower physics consisted in the advent of better detector systems allowing for multiparameter experiments with high-quality measurements of EAS quantities and of powerful tools to investigate the shower development in the atmosphere on the basis of elaborate theoretical models as well as the detailed performance of the detectors used. A standardization and improvement of those tools to the best of our knowledge is a vital prerequisite for a consistent comparison of results of different experiments.

We are convinced that a phase of improvement of the theoretical understanding, of the methodical progress, and of the technical advancement will inevitably be followed by a phase of interesting physics results.

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Figures

Fig. 1: left: pseudorapidity densities $\eta$ per wounded nucleon. right: central pseudorapidity densities $dN/d\eta$ ($\eta \approx 3.25$) vs. total multiplicity $n_{\text{prod}}$ [23]. VENUS without re-interaction reproduces the data better than VENUS with re-interaction.

Fig. 2: Proton structure function $F_2(x,Q^2)$ for low $Q^2$ and small $x$ as measured and predicted by various authors (see Ref. [1] and references therein).

Fig. 3: Probability distributions for the $\pi^0$ production as obtained by binomial statistics (for 10 pions in total) and hadron production via DCC.

Fig. 4: Layout of the FELIX detector.

Fig. 5: Inelastic proton-air cross-sections as a function of energy according to experimental data [65, 34, 84, 50, 7, 3] and to the models in CORSIKA and MOCCA.

Fig. 6: Comparison of the Fly’s Eye and the Yakutsk data on $X_{\text{max}}$ with simulation of the QGSJET model for pure p and Fe (solid line) and for the $\sum$ composition (dashed line, see text) [54].

Fig. 7: Comparison of the AKENO A1 data with simulations using MOCCA/SIBYLL for p and Fe (left) and the resulting fraction of Fe (right) as a function of primary energy [22].

Fig. 8: Is the composition changing or not? The answer depends on the yardstick (i.e. Monte Carlo program) used for comparison. Use the same yardstick to get consistent results, use a well calibrated yardstick to obtain the correct result.

Fig. 9: $N_{\mu}$ ($E_\mu > 1$ GeV) vs. $N_e$ from EAS-TOP for events selected “light” or “heavy” on the basis of TeV muons in LVD, compared with simulations for p and Fe nuclei [26].

Fig. 10: Flux of single hadrons as function of energy at 2200 and 110 m a.s.l. [4, 65].

Fig. 11: Hadron energy spectra for measured air showers with $4.0 < \log_{10}N_\mu < 4.25$. left: comparison with VENUS predictions for proton and iron primaries. right: same for SIBYLL calculations [47].

Fig. 12: Distribution of hadron energies normalized to the energy of the most energetic hadron per event $E_h/E_{h,\text{max}}$. When binning the events according to muon size (left) SIBYLL is not able to reproduce the experimental data. When binning according to the hadronic energy sum (right) there is fair agreement [48].

Fig. 13: Four independent analyses of the composition by the KASCADE Collaboration [78, 47, 48, 41, 21].
Fig. 14: Longitudinal shower development of hadrons in the KASCADE hadron calorimeter as compared to GEANT/FLUKA simulations [66].

Fig. 15: left: Scheme of an air shower hitting the Pamir emulsion chamber. Atmospheric photons are detected in the upper layer and hadrons produce secondary photons which are detected in the lower layer (from Ref. [58]). right: Example of a $\gamma$-family in a X-ray film (from S.A. Slavatinsky).

Fig. 16: Example of an event with a large halo (from S.A. Slavatinsky). It extends over several cm$^2$ corresponding to an energy of 50 PeV. The energy of the primary producing this event is estimated to be about 1000 PeV.

Fig. 17: Average optical density vs photon energy as obtained from GEANT simulations for different zenith angles. The errors of the points are typically 0.2 [42]. The shaded line indicates the calibration used by the PAMIR Collaboration.

Fig. 18: top: Example of a PAMIR event with aligned particle groups [14]. bottom: The most energetic CONCORDE event [18]. The circles indicate groups of individual particles.

Fig. 19: The emulsion chamber setup at Chacaltaya.

Fig. 20: Distribution of simulated events in the $N_h-Q_h$ plane. The plot contains 4200 events of different primaries with $30 \leq \sum E_\gamma < 100$ TeV. The new Centauro candidate is indicated with the large black dot.