Extensive Air Showers and Accelerator Data – The NEEDS Workshop

Ralph Engel\textsuperscript{a}∗†

\textsuperscript{a}Bartol Research Institute, Univ. of Delaware, Newark, DE 19716, USA.

Very high energy cosmic rays are typically studied by measuring extensive air showers formed by secondary particles produced in collisions with air nuclei. The indirect character of the measurement makes the physics interpretation of cosmic ray data strongly dependent on simulations of multiparticle production in showers. In April 2002 about 50 physicists met in Karlsruhe to discuss various aspects of hadronic multiparticle production with the aim of intensifying the interaction between high energy and cosmic ray groups. Current and upcoming possibilities at accelerators for measuring features of hadronic interactions of relevance to air showers were the focus of the workshop. This article is a review of the discussions and conclusions.

1. Introduction

The interpretation of most cosmic ray experiments relies on particle physics measurements done at accelerators. This is obvious in the case of measurements of cosmic rays with energies higher than $10^{15} \text{eV}$. At such energies direct measurements are very difficult or impossible because of low statistics due to the rapidly decreasing primary cosmic ray flux and limited detector aperture \cite{1}. However, utilizing the Earth’s atmosphere as target, large detector apertures and observation times can be achieved, extending the reach in energy up to $10^{20} \text{eV}$ and beyond. The drawback is the highly indirect method of measurement which is based on the detection of secondary particles, forming extensive air showers (EAS), and associated Cherenkov or fluorescence light.

The complexity of EAS requires the detailed simulation of hadronic and electromagnetic particle cascades. Whereas there is a good understanding of the predictions of QED on em. particle production, up to now, hadronic multiparticle production cannot be calculated on theoretical grounds. Although QCD is the accepted theory of strong interactions, only processes with large momentum transfer (hard scale) can be calculated reliably in perturbation theory. The majority of hadronic interactions are not characterized by a hard scale and do not fall into the domain of perturbative QCD. Therefore soft hadron production has to be simulated using phenomenological models. Naturally, due to the lack of a calculable theory, the predictions of currently used models on multiparticle production differ considerably. Measurements of hadronic interactions at fixed target and collider experiments are the ultimate and most efficient method to learn more about soft particle production. They are essential for tuning hadronic interaction models and reducing their uncertainties when extrapolated to ultra-high energy.

There are many open questions related to the primary cosmic ray spectrum. For example, the sources of the cosmic rays, the origin of the knee at $3 \times 10^{15} \text{eV}$ and the ankle at about $3 \times 10^{18} \text{eV}$, to name but a few, are not known. Many EAS measurements have been made to determine the mass composition of the cosmic rays in this energy region, which would help understand the origin of the knee. A compilation of the results expressed as mean logarithmic mass $\langle \ln A \rangle$ is shown in Fig. 1. To date there is no consistent picture of the compositional changes in the knee energy region, however there is general, qualitative agreement that the composition becomes heavier above $E \sim 3 \times 10^{15} \text{eV}$. One of the main reasons for the discrepancies between the different results is the


\textsuperscript{†}Present address: Forschungszentrum Karlsruhe, Institut für Kernphysik, Postfach 3640, 76021 Karlsruhe, Germany.
use of different hadronic interaction models in the analysis of the measurements (see also discussions in [2–4]).

There is urgency of improving the interaction between the high energy physics (HEP) and cosmic ray (CR) communities. Modern CR experiments have reached the statistics and precision that the simulation of hadronic interactions becomes one of the main limiting factors of the data analysis (for example, [7,8]). Even small differences in the assumptions on hadronic particle production in forward direction are of crucial importance for the analysis. On the other hand, many measurements of forward particle production, being most important for the simulation of particle cascades, can be done at current accelerators of moderate energy. In the course of concentrating all HEP capacities to few very high energy collider projects more and more low and medium energy experiments cease operation and will no longer be available for such measurements.

Discussing how accelerator measurements can help in understanding CR data, about 50 physicists met in Karlsruhe for the workshop Needs from Accelerator Experiments for the Understanding of High-Energy Extensive Air-Shower (NEEDS). The workshop was organized by Hans Blümer, Andreas Haungs, Heinigerd Rebel (Forschungszentrum Karlsruhe), and Lawrence Jones (Univ. of Michigan) and took place in the Research Center Karlsruhe on April 18 - 20, 2002. The following list gives an overview of the contributions.

- current situation regarding EAS and CR measurements
  (M. Roth, J. Knapp, E.C. Loh, O. Saavedra, G. Schatz, A. Haungs, M. Risse, M. Unger)

- relation of hadronic interactions to EAS observables and hadronic interaction models

- relevant data from current accelerator experiments
  (CDF @ Tevatron: V. Tano; H1 & ZEUS @ HERA: A. Rostovtsev, M. Erdmann; BRAHMS, PHOBOS, STAR & PHENIX @ RHIC: D. Bucher, E941 @ AGS: B. Fadem, HARP @ CERN PS: K. Zuber, G. Barr)

- planned accelerator experiments
  (TOTEM/CMS & ATLAS @ LHC: S. Tapprogge; CASTOR @ LHC: A. Angelis; MIPP @ Tevatron: C. Rosenfeld)

Further details, including presentations of the speakers, can be found on the workshop web page [9].

This article is an attempt to review the discussions of this workshop. In Sec. 2 a brief overview of the relevant interaction energies and regions of phase space of secondary particles is given. The current situation and problems of measuring primary CR energy and mass spectra are reviewed in Sec. 3, including the possibilities to assess hadronic interaction models. A number of accelerator experiments and measurements of relevance to EAS physics are discussed in Sec. 4. Some conclusions are presented in the last part of this article.

A summary of similar activities prior to this workshop can be found in [10,11].
2. Simulation of CR interactions: energies and phase space regions

Fig. 2 shows measurements of the primary CR flux and equivalent collider energies. For RHIC and LHC only the proton-proton collider option is shown. A detailed list of different acceleration options and their equivalent CR energies can be found in [11]. The energy of cosmic rays spans an energy range of more than 10 orders of magnitude and exceeds by far that currently available at man-made accelerators.

Interactions of highest energy cosmic rays open a window to ultra-high energy particle physics. In principle the analysis of EAS can yield information on multiparticle production in p-air collisions with CMS energies of up to 400 TeV. However, the features of the first interaction of a primary particle are largely washed out by the successive interactions of the secondaries with correspondingly lower energies. For example, Fig. 3 shows the number of successive interactions (generations) in a proton induced shower of $E = 10^{15}$ eV, which lead to the muons and hadrons observed at sea level. To obtain sensitivity to the physics of the first few interactions of the primary particle a good understanding of all subsequent interactions is needed.

One would expect that, because the energy of the knee corresponds roughly to that of the Tevatron collider, there is little uncertainty in modeling hadronic interactions up to this energy. This is not the case as modern collider experiments are designed to measure quantities which can be predicted within perturbation theory. Mainly hadronic processes with at least one hard scale (large mass or high virtuality) are studied. The measurement of hard processes requires typically high beam luminosities and sensitivity to secondaries with large transverse momentum. By contrast, particle production in cosmic ray cascades is dominated by the most energetic particles with small transverse momenta. The situation is shown in Fig. 4 by comparing the energy flow in p-p collisions at different collision energies with the phase space covered by the CDF and DØ detectors. In addition, measuring particles with momenta close to the beam direction is technically challenging. The mean transverse momentum of the secondary particles rises only very slowly with collision energy. This means that
the detectors have to be placed the closer to the beam pipe the higher the energy of the collision is to cover a similar phase space region.

In summary, EAS and more generally cosmic ray interactions can only be understood and analyzed successfully if hadronic interaction models are developed, tuned to data, and maintained that

(i) cover the entire range of relevant energies extending from the particle production threshold to the energy of the primary cosmic ray,
(ii) give a good description of particle production in the forward direction, i.e. soft and diffractive interactions, and
(iii) allow the extrapolation of accelerator measurements to higher energies and to unmeasured phase space regions.

3. Cosmic ray data and interaction models

At the workshop numerous analyses demonstrated the strong dependence of the interpretation of cosmic ray data on the assumptions on hadronic multiparticle production. In the following we will concentrate on the impact of the hadronic interaction model on the composition analysis in the knee energy region.

The mass composition derived by the CASA-BLANCA Collab. [12], shown in Fig. 5 as mean logarithmic mass, is a typical example of the model-dependence of EAS results. Using different hadronic interaction models for analyzing the same EAS data leads to significantly different conclusions on the mass composition. The statistical uncertainties are much smaller than the systematic uncertainty due to the model dependence. It is clear that some of the used hadronic interaction models describe collider data better than others and a critical evaluation of the models is needed. First steps towards a systematic comparison of models were done in [13].

However, shortcomings of the modeling of hadronic multiparticle production are obvious even if the QGSjet model is used, which provides currently the best description of the data of the multi-component detector KASCADE. A similar spread of \( \langle \ln A \rangle \) values is found if different observables of the same data set are analyzed with this model. For example, Roth et al. find a range of \( \langle \ln A \rangle \approx 1.7 - 3 \) for \( E \sim 10^{16} \) eV, whereas an anal-
ysis based on electron and muon numbers gives a systematically lighter composition than an analysis using muon and hadron observables [14].

Figure 6. Mean trigger and hadron rates of the KASCADE detector. Shown are the observed rates and predictions obtained by varying the inelastic cross-section in QGSJet. The point labeled by $\sigma_{\text{CDF}}$ corresponds to a $p\bar{p}$ total cross-section as measured by CDF [15]. The other points are labeled by the relative change of the cross-section as compared to the QGSJet default extrapolation.

On the other hand, the quality of the description of CR data by simulations can also be used to characterize how well a given interaction model describes leading particle production. For example, the KASCADE detector allows the simultaneous measurement of many different quantities which can be used as model discriminator [16,17]. In particular the correlation of hadrons to other observables is sensitive to the assumptions made in the interaction models. The inelastic proton-air cross-section is a quantity that strongly influences the rate of hadrons observed in the detector. Increasing the cross-section not only reduces the number of hadrons reaching sea level but also reduces the predicted KASCADE trigger rate, which also depends on the number of muons, see Fig. 6.

Another example is the analysis of Pamir emulsion chamber data in [18]. Due to the high altitude of the detector ($4370\text{m}, X_{\text{det}} \approx 600\text{g/cm}^2$) earlier stages of the shower evolution and also lower primary energies can be measured. Fig. 7 shows the measured optical density distribution of high-energy secondary shower particles observed in the Pamir emulsion chamber experiment together with model predictions. Where available in CORSIKA [19], old and new model versions are shown. Larger optical density corresponds to higher particle energy. The energy threshold is about 4 TeV for photons and electrons, and 8 TeV for hadrons.

Finally it should be mentioned that the simulation of hadronic interactions at low energy is an important, integral part of any air shower simulation. In particular the number of GeV muons, one of the important energy estimators in EAS experiments, depends directly on the secondary particle multiplicity in $\pi$- and $p$-air interactions in the 100 GeV range. The typical energies probed in EAS muon production are given in Fig. 8. The histograms show the distribution of the energy of hadron $h_1$ inducing the “last” interaction producing a hadron $h_2$ that subsequently decays into a muon which reaches sea level ($X = 1033\text{g/cm}^2$)

$$h_1 + \text{air} \rightarrow h_2 + X; \quad h_2 \rightarrow \mu + X'.$$  \hspace{1cm} (1)

Most of the muons are produced in collisions with energies about 10 to 100 times larger than the muon energy. In addition, more than 80% of the muons are produced in pion-air and not $p$-air collisions. A recent analysis of interaction characteristics can be found in [21] and muon measure-
ments are compared to simulations, for example, in [22].

Figure 8. Energy of “last interaction producing muons that reach sea level [20]. Shown are the spectra of vertical EAS, induced by protons with $E = 10^{15}$ eV, for muons with energies greater than 1 and 100 GeV.

4. Present and future accelerator experiments

Parton density measurements at the HERA collider are of particular importance as input in all modern hadronic interaction models. They are the basis of the calculation of inclusive minijet cross-sections at high energy and are one important component for the multiplicity and cross-section extrapolations (see, for example, [23]). In addition, recently measured leading proton and neutron spectra are of direct relevance to EAS simulations. Assuming that the forward, leading baryon distributions in $p-\gamma$ collisions are independent of the target type one can compare HERA data to model predictions for $p-p$ collisions. The HERA data are the first measurement of leading baryons at energies greater than 400 GeV (Fig. 9).

Tevatron measurements at $\sqrt{s} = 1800$ GeV are a benchmark for all models. Unfortunately particle distributions and multiplicities measured so far are restricted to the pseudorapidity range shown in Fig. 4. The measurement of hadron distributions ($p$, $\pi$, and $K$) at large Feynman $x$ would allow a direct model comparison. The large theoretical uncertainty in the model extrapolations could be reduced by a measurement of rates and inclusive cross-sections of jets with a transverse energy as low as 5 GeV. Indeed it is the poorly known minijet cross-section which is one of the major parameters in contemporary models. First steps in this direction are the analysis of the soft underlying event in collisions with high-$p_T$ jets [26] and the measurement of events with multiple jets [27,28]. The CDF and D$\emptyset$ detector upgrades for Run II include the installation of forward detector components [29]. The measurement of inclusive hadron distributions, not only that of diffractive events, would be of great help for tuning EAS interaction models. It would also allow to reduce uncertainties due to other phenomenological assumptions made in simulation codes [30].

RHIC data on Au-Au collisions at 200 GeV/n
have underlined the limited predictive power of modern simulation programs. The observed central particle densities were about 20 - 30% lower than the theoretical expectations. RHIC heavy ion data are of interest to cosmic ray simulations as they offer a cross check of the theoretical concepts implemented in the simulation codes. Furthermore the high parton densities in heavy nuclei at RHIC energy are expected to be comparable to that in light nuclei at correspondingly higher energy. Heavy ion experiments typically select events according to the centrality of the collision whereas for EAS simulations minimum bias measurements are preferred. Some of the detectors have coverage of a part of the forward direction [31]. The BRAHMS and STAR detectors allow particle identification up to $\eta \approx 3.7$. Multiplicities can be measured with PHOBOS up to 5.5 in pseudorapidity. A particularly interesting option would be the installation of N$_2$ or O$_2$ gas targets.

The new RHIC data have raised a number of questions and competing model approaches are developed for their explanation. A discussion of recent RHIC results can be found in [32] and their importance for EAS simulations is analyzed in [33].

The inelastic p- and $\pi$-air cross-sections are very important parameters of EAS simulations (see, for example, Fig. 6). Unfortunately the measurements available from Tevatron allow for a wide range of different extrapolations. The arising uncertainty translates directly to predictions for air showers. As shown in Fig. 10, the difference in the $\langle X_{\text{max}} \rangle$ predictions increases to more than 20 g/cm$^2$ at $10^{17}$ eV. This difference has to be considered as a lower limit since it corresponds only to the change of the proton and pion interaction lengths with air and not any additional model changes.

An accurate measurement of the p-p cross-section at LHC by the TOTEM Collab. [34] would restrict the extrapolations and hence improve the predictive power of currently used models. An interesting option is the combination of

\[ \sigma_{\text{tot}} = 81.83 \pm 2.29 \text{ mb} \]

The CDF Collaboration obtained a value which is considerably greater than those reported by E710 and E811 [15] ($72.81 \pm 3.1 \text{ mb}$ and $71.71 \pm 2.02 \text{ mb}$, respectively).

![Figure 10. Upper panel: two cross-section extrapolations which are compatible with the currently available Tevatron cross-section measurements. Lower panel: predictions for the position of the shower maximum, $\langle X_{\text{max}} \rangle$, using the two cross-sections. For comparison also the expectation of iron-induced showers are shown.](image)

the TOTEM and CMS detector readout which would allow for the combined analysis of events. In such a scenario the analysis of leading particles would be possible, within a restricted phase space range, in minimum bias measurements.

All LHC experiments will have the potential to contribute to minimum bias measurements in the central region [35]. The phase space regions covered by the ATLAS and CMS detectors are very similar, $|\eta| < 2.5$ with particle tracking and $|\eta| < 5$ with hadronic and em. calorimeters. LHCb will offer particle identification in the range $1.9 < \eta < 4.9$. In general there is a lack of forward detectors (the FELIX proposal of a dedicated detector for forward measurements was not
approved [36]).

One of the general problems will be the high luminosity, causing numerous independent p-p interactions per bunch crossing. Therefore the minimum bias measurements needed for event generator tuning have to be done when the collider starts operating and the luminosity is still low. From the point of view of air shower physics the acceleration of light ions would be of greatest interest, in particular asymmetric beam configurations such as p-C.

An example of a dedicated forward detector is the Castor project, planned as subdetector at CMS. It is designed to measure the ratio of electromagnetic to hadronic energy in the forward region (app. $5.5 < \eta < 7.2$) [37]. Options to increase the angular and momentum resolution of this detector to enhance its physics potential are currently studied.

There are a number of important low-energy experiments which help fill in gaps in measured data (see, for example, [38]) or improve the precision of available data. Whereas measurements of p-N collisions are most important for understanding inclusive neutrino and muon production, pion initiated reactions dominate in EAS.

The HARP experiment, motivated by the physics of atmospheric neutrinos, is designed to measure secondary hadrons, including particle identification, with virtually full phase space coverage [39]. Various particles (p, $\pi^\pm$, and K$^\pm$) are scattered off nuclear targets including nitrogen and oxygen. The beam energies range from 2 to 15 GeV. A related experiment [40] took data at 100 and 158 GeV using a modified setup of NA49.

Another dedicated low-energy experiment with full particle identification is MIPP (E907) at Fermilab [41]. It will use the main injector and allow the investigation of interactions induced by p, $\pi^\pm$, K$^\pm$ and $\bar{p}$ on a variety of nuclear targets ranging from H$_2$ to Pb. The beam energy will be between 5 and 120 GeV.

Some of the experiments at the Brookhaven AGS measure leading particle distributions in p-A interactions [42]. These measurements were motivated by the anomalously strong stopping power of baryons observed in heavy ion collisions. For example, new data by the E941 Collab. on leading proton and neutron spectra in p-Be collisions at 12 and 19 GeV cover almost the entire large $x$ region [43].

Similar studies were made at the SPS beam by NA49. The NA49 analyzed the leading proton distribution in p-p, p-Pb, and Pb-Pb collisions at 158 GeV per nucleon by comparing them to $\pi$-p interactions at the same energy [44]. (Unfortunately there are no NA49 results for light target nuclei such as Be or C available so far.)

The HERA-B experiment, designed to study B-meson physics, can also measure minimum bias particle production in p-C collisions. With its beam energy of 920 GeV and particle identification in the range $|x_F| \lesssim 0.4$ it can provide important constraints for EAS and muon flux simulations.

Finally it should be mentioned that the precise measurement of the inclusive atmospheric muon flux by L3+Cosmics [45] gives new insights into the description of forward particle production in p-air collisions in the 1 to 10 TeV energy range. In fact, no contemporary EAS Monte Carlo model can reproduce this measurement [46].

5. Conclusions and outlook

The current lack of methods for calculating QCD predictions for soft particle production at high energy necessitates the use of phenomenological models and assumptions. In modern CR experiments the uncertainty in the simulation of hadronic interactions has become the dominant source of systematic errors, which are difficult to estimate. Two types of data can help tuning interaction models, namely measurements of

(i) general properties of (forward) hadron production, and

(ii) particular predictions of models to test the underlying assumptions.

Whereas the former one serves mainly the adjustment of parameters of the models, the latter one validates the model concepts and increases the confidence in the extrapolations.

It is clear that the measurement of minimum bias hadron production in proton and pion induced collisions with light nuclei tops the priority list (i) of needs for EAS simulations. In particu-
lar data of fast secondary particles, both charged
and neutral, would be important. At high energy
proton or ion induced reactions are of primary in-
terest whereas at low energy beams of pions and
kaons are better suited.

All Monte Carlo codes use parametrizations
for the production of the leading baryons which
are assumed to scale with energy, up to effects
due to energy-momentum conservation. These
parametrizations are tuned to p-p data at fixed
target and HERA energies and should be consid-
ered as educated guess only. On one hand mod-
els for hadronic multiparticle production cannot
be used at low energy as the underlying assump-
tions are not applicable in this range. Thus, for
tuning the high-energy extrapolation of models,
p-nucleus data at energies below 200 GeV is of
limited use only. On the other hand high-energy
data of leading baryons in p-nucleus interactions
is not available.

Transverse momentum spectra of particles are
mainly of interest at low interaction energies. At
high energy the scattering angle of most of the
secondary particles is negligible and does not con-
tribute to the lateral extent of EAS. Therefore
data will be well-suited if high-energy measure-
ments are integrated over $p_{\perp}$.

The measurement of proton- and pion-nucleus
cross-sections is important as these cross-sections
influence the absorption in the atmosphere. The
corresponding proton measurements at acceler-
ators cover the energy range up to 400 GeV but
pion beam data is virtually absent.

Finally, recalling that ions in the range from He
to Fe are dominating the cosmic ray spectrum,
it should be emphasized that the measurements
outlined above done with ion beams are of great
interest, too. Ideally, the measurements should
integrate over all impact parameters and not be
restricted to central collisions.

The list (ii) is more model specific but the in-
clusive minijet cross-section and its energy depen-
dence are key observables for all models. Simi-
larly, parton densities at low $x$ and investiga-
tions of the range of applicability of perturbative QCD
will contribute to the reliability of the model ex-
trapolations.

The discussions at the NEEDS workshop
clearly showed that both the HEP and the CR
communities are interested in a closer collabora-
tion. However, dedicated measurements of data
relevant to EAS simulation will only be done if
the data potentially help to analyze the cosmic
ray measurements with significantly better accu-
rracy. More work has to be done to make the
interests and needs of cosmic ray physics more
transparent to the HEP community.

Accelerator experiments principally offer access
to their data and resources to cosmic ray col-
leagues. However, as is the case in general, also
projects of measurements at colliders are sub-
ject to evaluation, approval or rejection by com-
mittees and therefore have to be based on well-
deﬁned physics objectives and competitive, cost-
effective designs. Therefore any form of active
involvement of institutes or members of the cos-
mic ray community in form of

- sending people to accelerator experiments
to help performing measurements and data
analyses and

- financial support and cooperation

will be highly appreciated and is the best way to
improve recognition of the EAS simulation prob-
lems.

Systematic studies of the uncertainties in
contemporary hadronic interaction models are
needed to work out the most sensitive observ-
ables whose measurement will allow to improve
the physics descriptions and reduce the uncER-
tainties of the extrapolations in energy and phase
space. The publication of the results of such in-
vestigations is important for future reference and
justifying funding proposals.

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