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THEORY OF HADRONIC INTERACTIONS AND ITS APPLICATION TO MODELING OF COSMIC RAY HADRONIC SHOWERS*

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Cosmic ray showers offer a mean to study flux, particle type and arrival direction of primary cosmic rays at high energy. Such showers are formed by successive and competing particle interaction and decay processes. Detailed understanding of hadronic and electromagnetic particle production processes is needed to link the observed shower characteristics to properties of the primary particle. In this contribution we discuss some aspects of hadronic interaction models used in extensive air shower simulation and the importance and complementary nature of accelerator and cosmic ray measurements for improving these models.

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1. Introduction

Hadronic interactions form the core of cosmic ray induced showers by producing secondary particles that interact again, leading to an increase of the number of hadronic particles, or decay and thus feed the electromagnetic and muonic shower components. In the following we will consider the role of hadronic interactions in forming extensive air showers, whose observations provide some access to information on primary cosmic rays.

The energies of hadronic interactions in extensive air showers range from the particle production threshold ~ 1 GeV to the highest observed energies exceeding 10^{20} eV. In Fig. 1 we compare the CMS energies of current accelerators to the nucleon-nucleon CMS energy of cosmic ray interactions, assuming the primary particle is a proton. At low energy most of the cosmic rays are protons but the elemental composition is only poorly known for $E > 10^{14}$ eV (see [2,3]).

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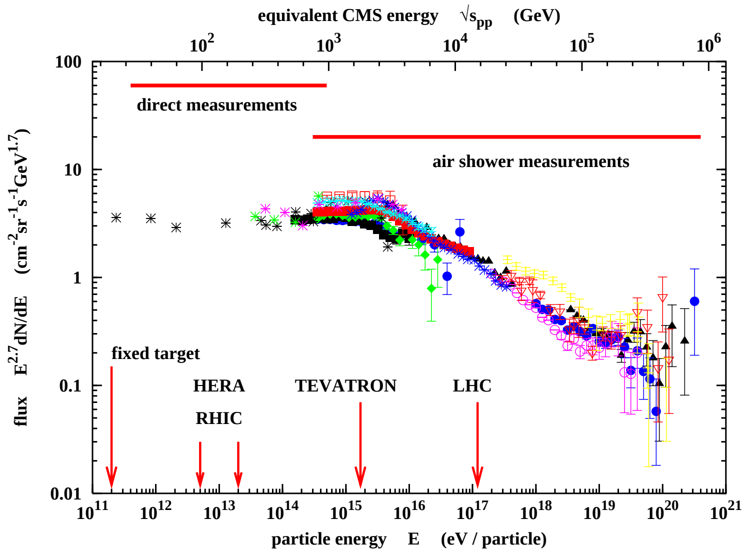

Fig. 1. All particle cosmic ray flux scaled by $E^{2.7}$. References to the measurements shown can be found in [1,2].

On one hand, understanding air showers at high energy is needed for studying the cosmic ray energy spectrum, composition and potential sources (*e.g.* [4]). On the other hand, interactions at energies greater than $\sim 2\times10^{15}$eV are interesting because they provide a window to particle physics beyond the reach of current colliders. However, measurements of extensive air showers provide only information on the bulk of the secondary particles, such as the maximum number of charged secondary particles (shower size at maximum), the atmospheric depth of shower maximum or the number of electrons and muons reaching the detector level. These secondary particles are the result of many hadronic and em. interactions. For example, a 10^{15} eV proton, initiating an air shower, undergoes typically more than 8 successive interactions with decreasing energy before it reaches sea level or gets stopped. In each interaction it transfers on average more than 60% of its energy to secondary particles.

The superposition of many interactions at different energies makes air showers rather insensitive to the initiating particle type and particular characteristics of the first interaction in a shower. This is an advantageous feature as long as only a rough estimate of the energy and composition of the primary particle is of interest. On the other hand, a precise measurement of the primary cosmic ray flux and composition is very difficult and relies on the detailed understanding and accurate simulation of hadronic interactions at all energies up to the cosmic ray energy under consideration [5–7].

2. Theory and models of hadronic interactions

In contrast to electro-magnetic interactions, which can be calculated within QED perturbation theory, most hadronic multiparticle production processes are in their nature non-perturbative. Therefore phenomenological models have been developed that combine general theoretical constraints such as unitarity and analyticity with parametrizations of experimental data. Based on the energy range of applicability, low- and high-energy models are distinguished.

Low- or medium-energy models are GHEISHA [8], the Hillas splitting algorithm in various implementations [9], FLUKA [10], UrQMD [11], TARGET 1.0 [12] and 2.1 [13], and HADRIN and NUCRIN [14]. These models are, to a large extent, theory- or phenomenology-motivated parametrizations of accelerator data and will not be discussed here.

Numerous high-energy models are available, including QCD-inspired Monte Carlo codes. However, models commonly used in high energy physics experiments are mostly not suited for air shower calculations. They either do not cover the required projectile-target combinations or are optimized for a good description of slow particles only (*e.g.* [15]). Currently the following models provide the most up-to-date description of hadron production as needed in air shower simulations: DPMJET II.5 [16] and III [17], neXus 3.0 [18], QGSjet 01 [19, 20], and SIBYLL 2.1 [21].

A review of the general physics assumptions underlying QCD-inspired high-energy models can be found in [22] and a brief introduction to relevant aspects of Regge theory, one of the foundations of these models, is given in [23]. All models are based on a detailed description of proton-proton collisions that is, employing Regge factorization, extended to other hadronic projectile/target combinations. In a next step Glauber–Gribov scattering theory [24] is used to model hadron-nucleus and nucleus-nucleus interactions in terms of the model elements previously developed for proton-proton collisions.

High-energy models for air showers have to extrapolate particle production in energy by several orders of magnitude. This extrapolation is highly uncertain due to the lack of a calculable theory of strong interactions. An additional complication is that the important phase space regions of particle production are not measured in current collider experiments (see Sec. 3), making the tuning of model parameters difficult.

In the following we will only comment on one of the important conceptional problems common to all models mentioned above, the extrapolation of minijet production to high energy. Other aspects of modeling hadronic multiparticle production are discussed, for example, in [22, 25].

A direct consequence of the partonic interpretation of hadrons is the production of particle jets in high-energy collisions. If the transverse momentum, $p_\perp$, of the scattered partons is of the order of several GeV these jets are called minijets. At very high energy (approx. $E > 10^{16}$ eV) the production of minijets begins to dominate the characteristics of particle production. The inclusive cross section for minijet production is calculable within perturbative QCD but depends strongly on the transverse momentum cutoff, $p_\perp^{\rm cutoff}$, needed to restrict the $p_\perp$ integration to the perturbative domain. Fig. 2 shows the inclusive cross section for minijet pair production in p–p collisions for several values of $p_\perp^{\rm cutoff}$, revealing one of the main weaknesses of the QCD-minijet picture. Perturbative QCD does not make a quantitative prediction of the range of its applicability. A closely related issue is the question of extrapolating parton densities beyond the measured range.

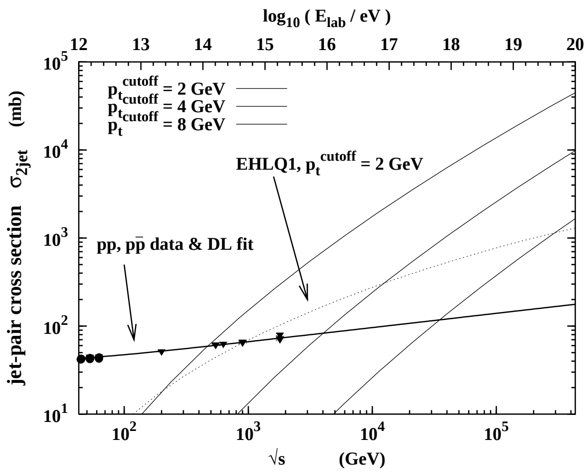

Fig. 2. Inclusive minijet cross section calculated for different minimum transverse momentum cutoffs. For comparison also data on total p-p and p-$\bar{p}$ cross sections are shown together with the Donnachie–Landshoff (DL) model [26].

Models based on parton densities proposed before HERA data became available, for example version 1.7 of SIBYLL described the increase of the total cross section using $p_\perp^{\rm cutoff}$ as free but energy-independent parameter [21]. The dotted curve labeled EHLQ [27] in Fig. 2 shows a minijet cross section similar to that of SIBYLL 1.7. However, HERA data [28] require a steeper rise of the minijet cross section, as indicated by the three other curves calculated with the GRV98 parton densities [29]. Keeping the hadronic interaction model unchanged the use of up-to-date parton densities would lead to more than 20 times more minijets at the highest energies, increasing the secondary particle multiplicity by roughly the same factor!

The steep rise of the minijet cross section is not compatible with the simple picture of many independent partonic interactions in a single proton-proton collision. The high parton densities obtained by extrapolating HERA measurements are expected to be tamed, and hence the minijet cross section be reduced, by non-linear effects [30]. These effects could be parton-parton fusion or even parton density saturation and are currently subject of intensive research [31]. The limited understanding of non-linear effects makes a reliable prediction of minijet cross sections at high energy impossible and any model extrapolation highly uncertain. Therefore, from the theory point of view, none of the high-energy extrapolations of the models (QGSJET: very high multiplicity, DPMJET, SIBYLL: medium multiplicity, neXus: low multiplicity) can be favored or excluded.

3. Constraints from accelerator data

There are a number of qualitatively different constraints coming from accelerator experiments: *(i)* measurements contributing to the general understanding of particle production, *(ii)* multiparticle production data of projectile- and target-combinations that form or are related to building blocks of the models, and *(iii)* data of hadron– and nucleus–nucleus and interactions that actually take place in cosmic ray cascades.

As already mentioned previously, HERA data on structure functions [28] have changed our view of the high-energy extrapolation. Similarly fundamentally important is the understanding of the new RHIC data [32] in terms of saturation effects. Only a combination of the structure function measurements with a reasonable model for non-linear effects due to high parton densities in nucleons and nuclei will allow a sensible extrapolation of current data to ultra-high energy.

Interestingly, whereas the RHIC data clearly showed for the first time a strong reduction of the secondary particle multiplicity in central Au-Au collisions, the direct impact of this effect on cosmic ray cascades seems rather small. Only a small fraction of central collisions is affected and mainly the production of slow particles is altered [33]. In air showers the most energetic particles determine the shower evolution. Slow particles are of lesser importance. However, in the black disk limit the large number of slow partons might even influence the leading particle spectrum [34].

Extensive comparisons of hadronic interaction models with data have been published by the corresponding model authors and also in [5]. Due to the lack of data these studies are mainly restricted to p–$\bar{p}/p$ and π–p interactions. It has been shown that the latest versions of the models give a good description of most data up to Tevatron energy. Already the comparison of the model predictions at LHC energy reveals large discrepancies in the extrapolation, see Fig. 3. The left panel of Fig. 3 represents the signal typically measured in high energy physics detectors, transverse energy or particle multiplicity. The right panel shows an observable relevant to air shower physics, the energy flow. Modern LHC detectors with acceptance ranges of about $|\eta| < 3$ will not allow the measurement of the phase space of most importance to cosmic ray cascades. To make matter worse, there is no one-to-one correlation between model predictions for the central rapidity range and the corresponding leading particle production. Only additional instruments such as TOTEM and CASTOR could provide the data needed by current and forthcoming cosmic ray experiments.

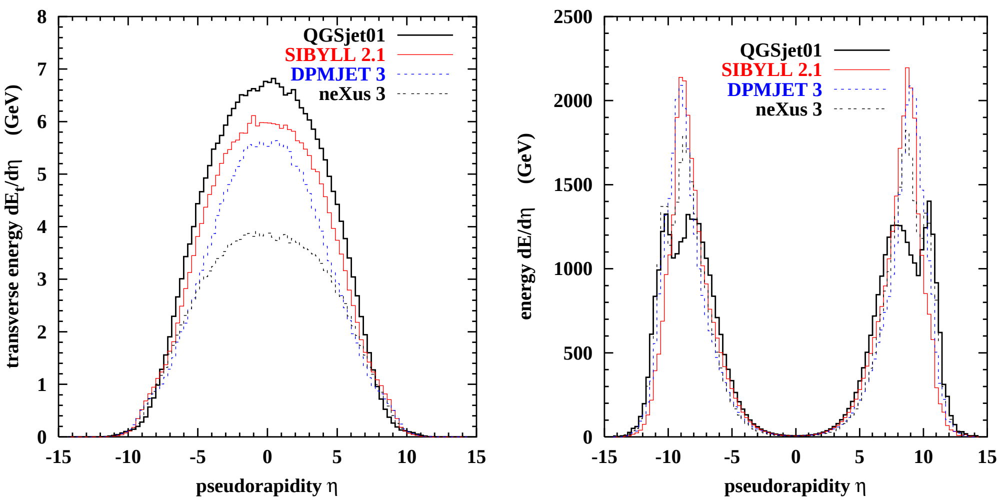

Fig. 3. Predicted transverse and total energy distributions for p–p collisions at LHC energy.

Over the last years the interaction between cosmic ray and high energy physics experiments intensified. A good example is the NEEDS workshop [35], which brought together representatives of both communities. Meanwhile there are many fixed target experiments with large acceptance detectors that are in the process or plan to measure interactions with projectile/target parameters similar to those found in air showers [36].

4. Constraints from cosmic ray data

The complexity of cosmic ray showers makes the derivation of absolute constraints on particle production models nearly impossible. Still there are a number of possibilities to either check the consistency of a model with data or to obtain limits which are weakly model-dependent.

Measurements of the inclusive muon flux, produced by the interaction of cosmic rays in the upper atmosphere, are well-suited to test hadronic interaction models in the energy range from ~ 10 GeV to more than 10 TeV (for example, [37–40]). Due to the steeply falling spectrum of the primary cosmic ray flux most of the muons stem from the decay of pions and kaons produced in the first interaction. The major source of uncertainty in such calculations comes from the limited knowledge of the primary cosmic ray flux.

Other tests of hadronic interaction models are, for example, the comparison of predicted and measured correlations between different shower components, see [41]. Similarly the muon energy spectrum within air showers is sensitive to the characteristics of hadron production over a wide energy range. First comparisons by KASCADE indicate that none of the models gives an adequate description of their measurements [42].

Extensive air showers can be used to measure the proton-air cross section at very high energy [43–45]. As the cross section cannot be measured directly, simulations are needed and introduce some unavoidable model dependence [46, 47]. Conversely, if the cross section were known from other sources, air shower data can be used to characterize high-energy hadron production qualitatively [48].

As a final example we show in Fig. 4 two possible extrapolations of the SIBYLL model [36]. In one case (model I) an energy-dependent transverse momentum cutoff for the perturbative part of the model and correspondingly small minijet cross section are used. Model II extrapolates the minijet cross section with a constant transverse momentum cutoff leading to a faster rising minijet cross section. The impact on the cross section predictions of both models is demonstrated in the left panel of Fig. 4. Both models are compatible with currently available Tevatron data on particle multiplicities and cross sections. The right panel of the same figure compares model-independent measurements of the mean depth of shower maximum of extensive air showers. Given the poorly known composition at high energy, two calculations for proton and iron induced showers were performed using model I. The data lie well within the model predictions. The rapid increase of the cross section of model II leads to significantly shallower depths of maximum of the corresponding showers. Model II is also compatible with the shown data, however, an increase of the p–$\bar{p}/p$ cross section faster than that of model II seems to be disfavored.

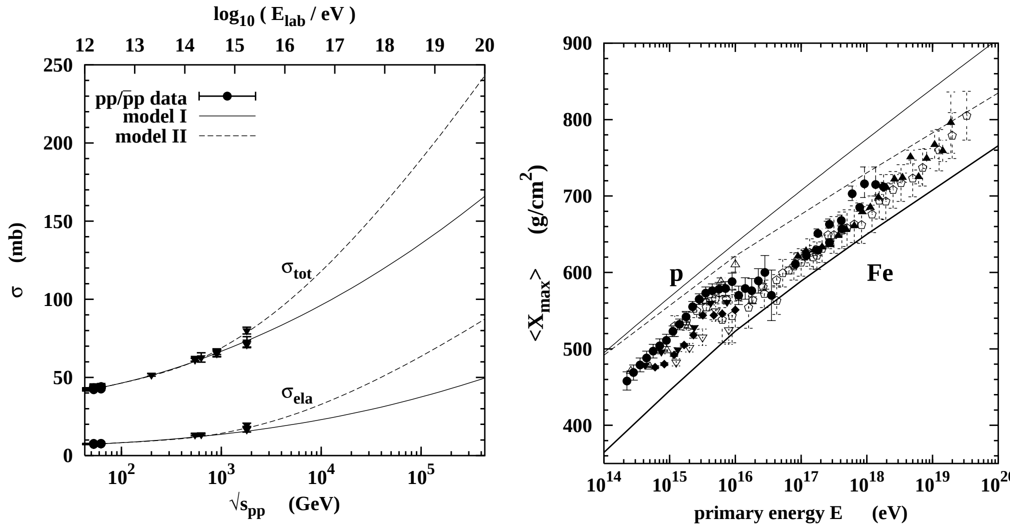

Fig. 4. Left panel: comparison of model results with data on total and elastic p–p and p–$\bar{p}$ cross sections. Right panel: model predictions on mean depth of shower maximum $X_{\max}$ (for references to the exp. data see, for example, [1]).

5. Summary

The indirect method of measuring cosmic rays via extensive air showers depends crucially on the simulation of hadronic multiparticle production to understand the relation of shower observables to properties of the primary particles. At the same time the energies of cosmic rays can exceed by far those reached at man-made accelerators, providing an opportunity to study particle physics at extreme energies.

Over the last decade significant progress has been made in developing sophisticated interaction models. However, due to the non-perturbative character of hadronic multiparticle production, these models are largely based on phenomenological assumptions and are characterized by many free parameters. Minimum bias measurements of multiparticle production in fixed target and collider experiments are of prime importance for verifying model assumptions and tuning free parameters.

The extrapolation of particle production within modern hadronic interaction models is still highly uncertain, although perturbative QCD is utilized as an important theoretical input. Further measurements at current and planned accelerators are needed to improve this situation, in particular measurements of leading particle production are important for air shower physics.

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