

HADRON PHYSICS: RECENT RESULTS FROM COSMIC RAY EXPERIMENTS*

HANS P. DEMBINSKI

Bartol Institute, Dept. of Physics and Astronomy, University of Delaware
217 Sharp Lab, 104 The Green, Newark, DE 19716, USA

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Finding an accurate model of soft hadronic interactions is of great interest for the field of astroparticle physics. Most ground-based astroparticle experiments deal with air showers initiated by cosmic rays in Earth's atmosphere, either as signal or as an important background. I discuss the importance of hadron interaction models for air shower experiments, and summarize recent tests of current models performed by the Pierre Auger Observatory, Telescope Array, and the IceCube Neutrino Observatory.

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1. Introduction

The Earth is constantly hit by a flux of high-energy cosmic rays, charged particles of astrophysical origin, with an energy spectrum from GeV to hundreds of EeV. Cosmic rays above 0.1 PeV are too rare and too energetic to be observed directly by space-based experiments. Instead, these cosmic rays are detected through air showers, cascades of secondary particles created by interactions with Earth's atmosphere.

Collisions of EeV cosmic rays with nucleons in the atmosphere have huge centre-of-mass energies beyond the reach of current colliders. For example, the centre-of-mass energy in a nucleon–nucleon interaction of a 1 EeV (10 EeV) cosmic proton is 43 TeV (137 TeV). An accurate theoretical description of these interactions is of great scientific interest, since air shower experiments rely on it to infer the properties of the cosmic ray from the detectable secondary particles generated in the air shower. Interactions with the small transverse momentum transfer drive the shower development. They cannot

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be described in the framework of perturbative quantum chromodynamics, and they are not well measured at colliders, since collider experiments mostly focus on central interactions with high momentum transfer.

Predictions are made with phenomenological models based on collider data. The underlying idea of most models is that projectiles are split into partons, which interact by forming colour-neutral strings between them. The strings, which have a constant tension, rupture once the local energy density overcomes the mass threshold to produce hadron pairs. This idea describes many experimental features, but its predictive power is limited. Models are tuned to available collider data and then extrapolated into the phase-space regions relevant for air showers. The theoretical uncertainty on how to do the extrapolation is reflected in the variety of hadronic interaction models available on the market [4–7].

Since progress on the hadronic interaction models is so important for the field of astroparticle physics, air shower experiments test models, by comparing predictions for different air shower observables with data. Moreover, the proton-air cross section has been measured with fluorescence telescopes. In both cases, analyses are hindered by the unknown mass composition of cosmic rays. Usually, a change in an air shower observable can be explained either by a change in a hadronic model or by assuming a different mass composition. To resolve this ambiguity, tests focus on combined predictions for more than one air shower observable.

The latest generation of air shower experiments are hybrid detectors, sketched in Fig. 1. The leading experiments in the ultra-high energy regime

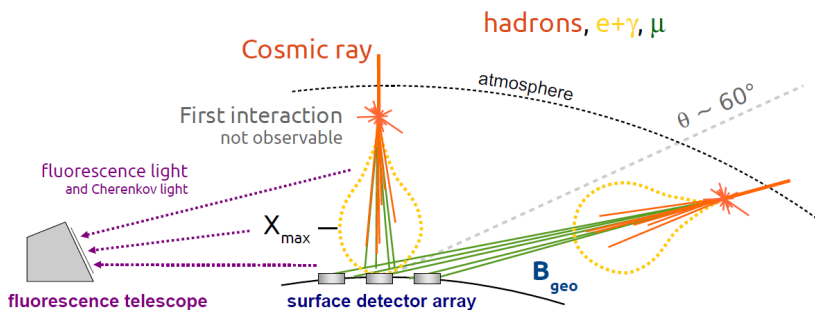


Fig. 1. Sketch of a modern hybrid air shower detector, together with a vertical and a highly-inclined air shower, generated by interactions of high-energy cosmic rays with Earth’s atmosphere. Detectable particles at the surface are mainly electrons, photons, and muons. Fluorescence telescopes observe UV-light, generated primarily by quasi-elastic collisions of shower electrons with air molecules. An important observable is the depth $X_{\max}$, where the electrons are most numerous. Only the muonic component of a highly-inclined air shower reaches the ground. To some degree, muons get charge-separated by deflections in Earth’s geomagnetic field.

are the Pierre Auger Observatory [1] in Argentina, and Telescope Array [2] in Utah, USA. Hybrid detectors provide excellent opportunities to test hadronic models. They can perform complementary measurements of the same air shower, which increases the testable combinations of air shower observables. The IceCube Neutrino Observatory, shown in Fig. 2, is also a hybrid detector in that sense. While it is primarily a successful observatory for extra-terrestrial neutrinos [8], it combines a surface array, sensitive to air showers, with a km³-volume of clear ice instrumented with Cherenkov-detectors in 1.5 km depth. This unique configuration allows them to study TeV muons from the central core of an air shower in the deep detector, which are undetectable by other experiments.

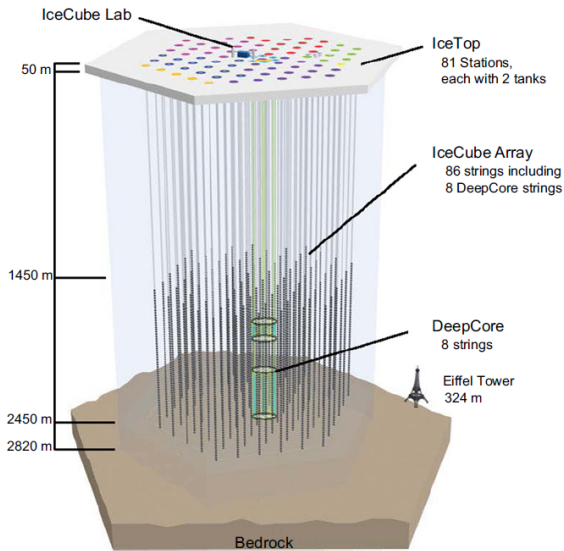


Fig. 2. Schematic view of the IceCube experiment. The bulk of the light detectors are buried under 1.5 km of ice and form the in-ice detector. The in-ice detector is used mainly for neutrino astronomy and neutrino physics studies. The IceTop sub-detector consists of 81 pairs of ice-filled tanks at the surface. They serve two purposes: vetoing particles from cosmic-ray induced air showers that reach the in-ice detector (non-neutrino events), and studies of cosmic rays.

I will summarize recent results from these three observatories that are used or will be used to test hadronic interaction models. We start with results based on the depth X_{max} of shower maximum, and then proceed to measurements of muons in air showers, which show the largest discrepancies between theory and experiment.

2. Results based on the depth of shower maximum

Fluorescence detectors measure the longitudinal profile of an air shower, mainly the electron density profile. The depth $X_{\max}$ of the profile where the density is at its peak can be measured very well and compared with air shower simulations based on hadronic interaction models.

p -air cross section. Both the Pierre Auger Observatory [9] and Telescope Array [10] have published measurements of the proton-air cross section. The first interaction cannot be directly observed, since it does not produce enough secondary particles, but its depth follows an exponential distribution with a decay-constant that can be computed from the cross section. The exponential tail is reflected in the $X_{\max}$ -distribution. Experiments fit the tail, which is mostly generated by cosmic protons, to extract the decay-constant. A small model-dependent correction is applied to account for distortions that arise from stochastic fluctuations in the shower development. The analysis is very sensitive to an admixture of cosmic helium, which would make the cross section appear larger than it truly is. The results are given under the condition that the helium fraction is small.

Moments of the $X_{\max}$ -distribution. The Pierre Auger Observatory [11] and Telescope Array [12] have published the mean and variance of $X_{\max}$. There has been a heated debate whether their observations are compatible. The observatories use different analysis strategies, with subtle differences that made them not directly comparable. The debate was settled recently by simulating how the $X_{\max}$ -distribution observed by the Pierre Auger Observatory would look like in Telescope Array [13]. The results were found to be in agreement with Telescope Array's own measurement.

The Pierre Auger Collaboration has also published an interpretation of the combined measurement of mean and variance of $X_{\max}$ in terms of mean and variance of the distribution of logarithmic mass $\ln A$ of cosmic rays [11,14]. The conversion depends on the hadronic model. There is a physically allowed region, that contains all possible combinations of mean and variance pairs ("umbrella plot"). The model QGSJet-II.04 [4] produces points that fall outside of the boundary, but are reconcilable with it, if the systematic uncertainty of the experiment is taken into account.

Component fits of the $X_{\max}$ -distribution. The Pierre Auger Collaboration has also published fits of their full $X_{\max}$ -distributions [15], based on a mass-composition model with up to four components. A goodness-of-fit parameter is used to test hadronic interaction models. The model QGSJet-II.04 again shows the largest tensions, which was expected from the umbrella plots. QGSJet-II.04 predicts a larger $X_{\max}$ -variance than other models, which seems to be at odds with the data.

3. Results based on muons in air showers

Muons in air showers are messenger particles of their hadronic origins. Their propagation through the atmosphere is light-like, which means that their space-time distribution at the ground retains information about their parent particles, which are mostly pions. The discrepancies between model predictions and observations are larger for muons, and in some cases the predictions are dramatically off.

Muon production depth. Shower muons propagate almost with the speed of light, and they are mostly generated very close to the shower axis. Approximately, they behave like light rays emitted from a point on the axis. This means that the production point can be computed from the location and arrival time of the muon at the ground, based on a simple geometrical analysis. The Pierre Auger Observatory has measured the average muon production depth [16] based on this approach. Only a small model-dependent correction has to be applied, if the shower geometries and the muon signals are carefully selected. Measurement and prediction are completely off in case of the model EPOS-LHC [5].

Muon content in highly-inclined showers. The Pierre Auger Observatory is sensitive to air showers with all inclinations. Highly-inclined air showers with zenith angles larger than 60° are muon-rich at ground level. Such showers, observed simultaneously in the fluorescence telescopes and in the surface array, have been used to measure the average size of the muon component [17]. A combined analysis of the muon content and $X_{\max}$ showed that none of the tested models produced enough muons to describe the data, even if systematic uncertainties of the measurement are taken into account.

Peripheral muons. IceTop, the surface component of the IceCube Neutrino Observatory, consists of water-Cherenkov detectors with very low signal thresholds. An ongoing analysis uses this detector to measure the average lateral density profile of muons in near-vertical PeV showers (see [18], and references therein). The detectors do not have direct particle identification capabilities, but GeV muons can be identified statistically. Their signal is proportional to the track length in the cylindrical detector volume. In vertical showers, the track length is equal to the detector height, which separates GeV muons from hits of other particles. The analysis is promising, since it provides the muon density over a large lateral range at a high altitude, and can be used to measure the muon attenuation with zenith angle. First results show that model predictions vary greatly with respect to each other, but at least bracket the measurement.

Muons with high p_T . The IceCube Neutrino Observatory is a tracking detector. It can separate individual tracks if their lateral separation is larger than the grid size. Rare events were found, which show two coincident parallel tracks. The events are interpreted as air shower events, where a

single muon with high transverse momentum p_T arrives together with a compact bundle of core muons. The frequency of these events as a function of the lateral separation has been published [19]. Simulation studies show, that the high- p_T muon is typically produced in the first interaction of a cosmic ray with the atmosphere. Simulation studies are currently under way to explore whether the data can be used to measure the p_T distribution of muons in proton–air interactions at the PeV scale [20,21].

4. Conclusions

Hybrid experiments, which measure complementary aspects of air showers, produce valuable data to challenge and test soft hadronic interaction models. Muons in air showers show the greatest discrepancies between experiment and theory, and need to be investigated further.

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