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Cosmic ray physics with the ARGO-YBJ experiment

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ABSTRACT

Cosmic ray physics in the 10^{12}–10^{15} eV primary energy range is among the main scientific goals of the ARGO-YBJ experiment. The detector, located at the Cosmic Ray Observatory of Yangbajing (Tibet, P.R. China) at 4300 m a.s.l., is a full coverage Extensive Air Shower array consisting of a carpet of Resistive Plate Chambers of about 6000 m^2. The apparatus layout, performance and location offer a unique possibility to make a deep study of several characteristics of the hadronic component of the cosmic ray flux in an energy window marked by the transition from direct to indirect measurements. In this work we will focus on the experimental results concerning the measurements of the primary cosmic ray energy spectrum and of the proton-air cross-section. The all-particle spectrum has been measured, by using a bayesian unfolding technique, in the 1–100 TeV energy region. The proton-air cross-section has been measured at the same energies, by exploiting the cosmic ray flux attenuation for different atmospheric depths (i.e. zenith angles). The total proton–proton cross-section has then been estimated at center of mass energies between 70 and 500 GeV, where no accelerator data are currently available.

1. Introduction

ARGO-YBJ (*Astrophysical Radiation with Ground-based Observatory at YangBaJing*) is a full-coverage Extensive Air Shower (EAS) array consisting of a single layer of Resistive Plate Chambers (RPC) of about 6000 m^2 [1,2]. It is located at the Cosmic Ray Observatory of Yangbajing (Tibet, P.R. China) at 4300 m a.s.l., corresponding to a vertical atmospheric depth of $h_0 \simeq 610\,\mathrm{g/cm^2}$. The scientific goals of the experiment include Very High Energy $\gamma-$ray astronomy with a few hundreds GeV energy threshold and cosmic ray physics in the 10^{12} –10^{15} eV primary energy range, where the transition from direct to indirect measurements occurs. The whole apparatus is logically divided into 153 units called *clusters* (7.64×5.72 m^2), each made by 12 RPC operated in streamer mode [3]. Each RPC ($1.26 \times 2.85\,\mathrm{m^2}$) is read out by using 10 pads ($62 \times 56\,\mathrm{cm^2}$), which are further divided into 8 strips ($62 \times 7\,\mathrm{cm^2}$) providing a larger particle counting dynamic range. The signals coming from the strips of a given pad are sent to the same channel of a multi-hit TDC. The whole system provides a single hit (pad) time resolution of about 1.7 ns, which allows a detailed three-dimensional reconstruction of the shower front with unprecedented space-time resolution. An analog RPC charge readout is also going to be implemented. This will allow the study of the cosmic radiation up to PeV energies.

2. Measurement of the all-particle energy spectrum

The experiment low energy threshold allows the study of the all-particle spectrum in a region usually covered by direct measurements. This is very useful in order to compare different techniques with completely different systematics. As an example, EAS experiments must rely on the shower simulations based on a given hadronic interaction model, while this is not the case for direct measurements. The all-particle spectrum was measured by means of an unfolding procedure based on the Bayes theorem. The results are briefly outlined in the following, more details can be found in Ref. [4].

The observed quantity is the strip multiplicity distribution $N(M)$, which represents the number of showers producing M fired strips in a given time interval ΔT and within a solid angle Ω. The number $N^A(E_i)$ of showers produced by primary cosmic rays with mass A and energy E_i can be related to the number $N(M_j)$ of events detected with a multiplicity M_j by using the following [5,6]:

$$N^A(E_i) \propto N(M_j)P^A(E_i|M_j) \tag{1}$$

$$P^A(E_i|M_j) = \frac{P^A(M_j|E_i) \cdot P^A(E_i)}{\sum_{l=1}^{n_E} P^A(M_j|E_l)P^A(E_l)} \tag{2}$$

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where $P^A(E_i)$ is the probability for a primary nucleus with mass A and energy E_i to produce a shower and $P^A(M_j|E_i)$ is the corresponding conditioned probability [4]. In this scheme, $P^A(M_j|E_i)$ must be computed by means of a Monte Carlo (MC) simulation. The all-particle energy spectrum $N^{all}(E_i)$ can be extracted from the $N(M_j)$ distribution by using Eqs. (1) and (2). The probabilities $P^{all}(M_j|E_i)$ were computed by using MC showers induced by protons and by helium, CNO and iron nuclei. The Bayesian analysis is performed by means of an iterative procedure that stops when further variations on the value of $N^{all}(E_i)$ are negligible.

2.1. Data analysis and results

The simulated events used in this analysis were generated by using the CORSIKA (ver. 6.7.10) code including QGSJET-II and GEISHA hadronic interaction models [7]. Events were generated with a power law energy spectrum in the range $(0.1-10^4)$ TeV. About 180×10^6 protons, 21×10^6 Helium nuclei, 10.5×10^6 CNO group and 10×10^6 iron nuclei were generated in the zenith angle range $(0^\circ-45^\circ)$. A full detector simulation based on the GEANT3 [8] package was then applied, including background, trigger and RPC efficiency, etc. Simulated events were reconstructed and analyzed by using the same code used for real data. The experimental data used in this analysis (75×10^6 events) were collected in the period January–May 2008, by the central 130 clusters and by using an inclusive trigger requiring at least 20 fired pads in a time window of 420 ns. A first data selection was based on the quality of the reconstruction procedure. Additional cuts were applied in order to have a small contamination of *external events* (i.e. showers with the core position outside the detector but misreconstructed inside) and to estimate with good accuracy the probabilities used in the unfolding procedure. For this purpose, events were required to have reconstructed zenith angle θ less than 30° and detected strip multiplticity M in the range $150 \le M \le 50\,000$. The rejection of *external events* was made by requiring the strip density in the innermost 20 clusters to be greater than that in the outermost 42. The fraction of events passing the cuts was about 21%, fully consistent with the MC predictions.

Simulated events were sorted in ten energy bins in the range $(0.55-288)$ TeV and fifteen bins in the multiplicity range $(150-50\,000)$. The same multiplicity bins were used to analyze the real data. The Bayesian unfolding was performed by using the probabilities $P^{all}(E_i|M_j)$ computed by means of the MC events. A recursive procedure was set and a soft smoothing was applied to the n-th value of the $P^{all}(E_i)$ in order to ensure a stable convergence [4]. The results of the intensities $N^{all}(E)$ of the all-particle energy spectrum are reported in Fig. 1, together with previous results from direct and indirect measurements [9]. The measured intensities are reported with the corresponding uncertainties obtained by taking into account both statistical and systematic errors. The total uncertainty on each experimental point turns out to be in the range (20–30)% [4]. As can be seen, ARGO-YBJ results are consistent with both direct and indirect measurements, this being another check of the reliability of the adopted technique. A new analysis, with enlarged statistics, is then currently being performed, in order to further reduce the associated uncertainties.

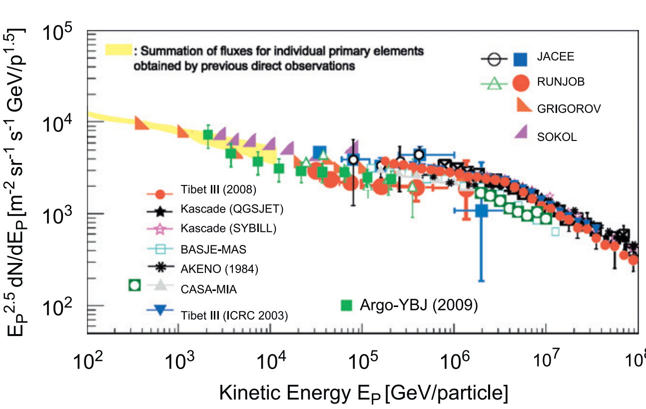

Fig. 1. The differential all-particle energy spectrum resulting from ARGO-YBJ data (including statistical and systematic uncertainties) together with previous measurements. The covered energy range allows the comparison of different techniques (direct and indirect measurements) with completely different systematics.

3. The proton-air cross-section measurement

The measurement is based on the shower flux attenuation for different zenith angles, i.e. atmospheric depths (see Ref. [10] for a complete description). The detector location (i.e. small atmospheric depth) and features (full coverage, angular resolution, fine granularity, etc.) ensure the capability of reconstructing showers in a very detailed way. These features have been used to fix the energy ranges and to constrain the shower ages. In particular, different hit (i.e. strip) multiplicity intervals have been used to select showers corresponding to different primary energies. At the same time the information on particle density, lateral profile and shower front extension have been used to select showers having their maximum development within a given distance/grammage X_{dm} from the detection level. This made possible the unbiased observation of the expected exponential falling of shower intensities as a function of the atmospheric depth through the $\sec\theta$ distribution. After the event selection, the fit to this distribution with an exponential law gives the slope value α, connected to the characteristic length Λ through the relation $\alpha = h_0/\Lambda$. That is:

$$I(\theta) = A(\theta)I(\theta=0)e^{-\alpha(\sec\theta-1)} \quad (3)$$

where $A(\theta)$ accounts for the geometrical acceptance of each angular bin. The parameter Λ is connected to the proton interaction length by the relation $\Lambda = k\lambda_{int}$, where k depends on hadronic interactions and on the shower development in the atmosphere and its fluctuations [11]. The actual value of k must be evaluated by a full MC simulation and it depends also on the experimental approach, the primary energy range and on the detector response.

Therefore the same procedure has been applied to the simulated sample, thus obtaining the value of Λ^{MC}. The value of k, which refers to each strip mutiplicity bin, can then be evaluated as $k = \Lambda^{MC}/\lambda_{int}^{MC}$, where λ_{int}^{MC} is given by the average value of the MC proton interaction length distribution, corresponding to the selected events in the considered multiplicity bin.

The measured interaction lengths are then obtained by correcting the observed lengths, Λ, by the factors k previously determined on the basis of the MC simulation: $\lambda_{int} = \Lambda/k$. Such values must then be corrected for the effects of heavier nuclei contained in the primary cosmic ray flux. In the present analysis, this has been made by evaluating the contribution to the slope α produced by the addition of a proper helium fraction to the proton primary flux in the MC simulation, the contribution of nuclei heavier than helium being negligible.

The p-air *production* [12] cross-section is then obtained from the relation: $\sigma_{p\text{-}air}\,(\text{mb}) = 2.41\times10^4/\lambda_{int}\,(\text{g/cm}^2)$, while several theoretical approaches can be used to get the corresponding p–p total cross-section σ_{p-p} [13].

3.1. Data selection and Monte Carlo simulation

The analysis was applied to a data sample of about 10^8 events collected by the 130 clusters of the central detector with a 20 pad threshold inclusive trigger. After a first selection based on the quality of the reconstruction, a dedicated procedure was set up in order to reject the background due to events having the real shower core outside the detector area but misreconstructed inside. This was performed by means of additional cuts essentially restricting the fiducial area and requiring a minimum detected hit density within a given distance R_{70} from the reconstructed core position. The quantity R_{70} was defined as the radius of the smallest circle (centered in the reconstructed core position) containing 70% of the fired strips and was required to be less than 30 m. Simulation showed that this last cut is also related to the shower development stage, allowing to constrain the value of X_{dm} (Fig. 2). The whole procedure finally selected $\sim 12\%$ of the events initially reconstructed with $\theta_{rec} < 40^\circ$ and $M \geq 500$, in agreement with MC predictions.

The surviving data sample was finally split into five different bins of fired strips M, each one corresponding to a different primary energy interval, starting from the threshold of at least 500 fired strips on the whole central detector in the trigger time window of 420 ns.

A suitable simulation chain was used in order to check the effects of the different analysis cuts and have an estimate of the possible systematics. About 10^8 proton initiated and 2×10^7 He initiated showers, with the proper power law energy spectra between 300 GeV and 3000 TeV and zenith angle up to 45°, were produced with the *CORSIKA* code [7], using three different hadronic interaction models, namely *QGSJET-I* [14], *QGSJET-II.03* [15], and *SIBYLL-2.1* [16]. A full simulation of the detector response, based on the GEANT3 package [8] and also including the effects of time resolution, trigger logic, electronics noise, etc., was performed. MC data have been analyzed by using the same reconstruction code as for real data. The reliability of the simulation procedure was successfully checked in several ways, concerning in particular the observables mostly involved in selection cuts and primary energy determination.

The primary energy value assigned to each strip multiplicity bin has been identified by the median value E_{50} of the corresponding distribution. It has been verified that the energy scale determined by E_{50} is equivalent to that given by the average of the Log(E) distribution.

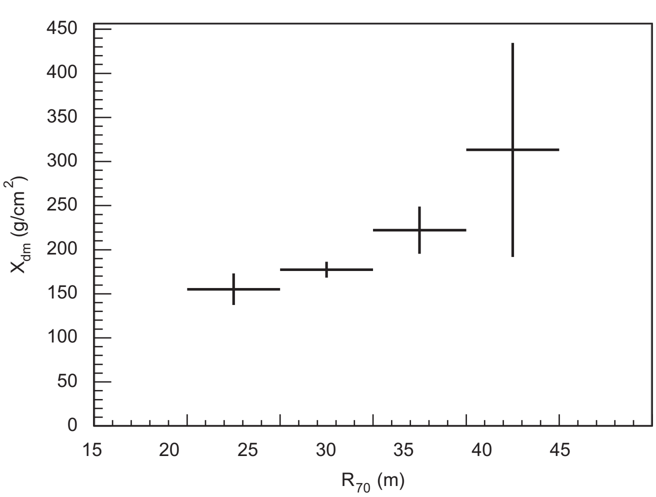

Fig. 2. Correlation between R_{70} and X_{dm}. The plot refers to proton initiated simulated showers.

Simulations have also shown that the residual contamination of external events is less than 1% for all the energy bins.

Finally, a check has been made that the event selection, both in primary energy and X_{dm}, was independent of the zenith angle up to about 40° thus verifying that our experimental sensitivity is not compromised by the shower-to-shower fluctuations [17].

3.2. Analysis results and discussion

The resulting sec θ distributions for the five energy intervals clearly show the expected exponential behavior (see Fig. 3). This is a further check that the detector capabilities and the adopted analysis cuts allowed a proper selection of events for the cross-section measurement.

The angular distributions obtained in the same way from the MC simulation show very similar behaviors to that of the real data and the same considerations can be applied. From them the values of k at each energy have then been obtained. For all the

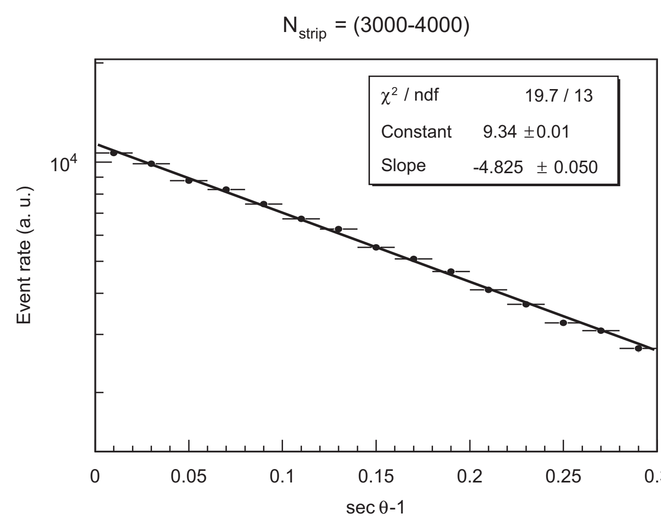

Fig. 3. Experimental *sec* θ distribution for one of the five strip multiplicity samples, after the selection cuts and the correction for the geometrical acceptance in each angular bin.

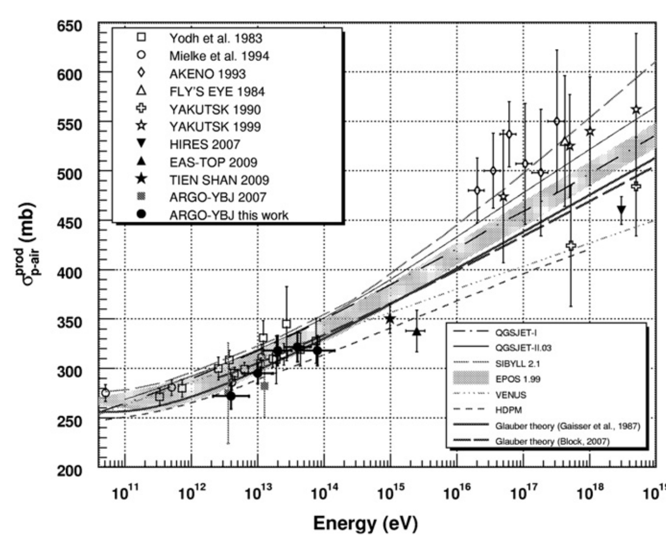

Fig. 4. The proton-air *production* cross-section as measured by ARGO-YBJ and by other cosmic ray experiments [10,18]. The predictions of several hadronic interaction models are also shown [10,19].

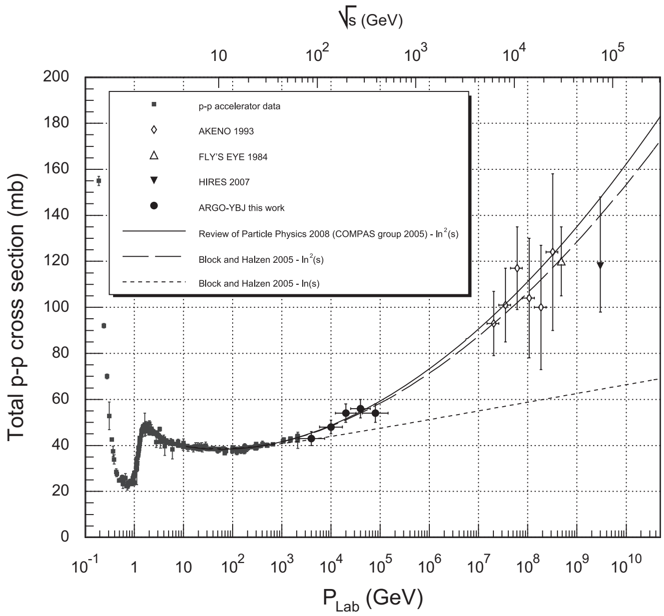

Fig. 5. The p–p total cross-section obtained by ARGO-YBJ [10], together with results published by other cosmic ray and accelerator experiments [22,23].

multiplicity samples $k \simeq 1.6-1.8$, apart from the values obtained at the boundaries of the covered energy region [10].

The effect of the cosmic ray primaries heavier than protons has been estimated as previously outlined. Different estimates of the primary fluxes [9] have been used in order to evaluate the correction factors to be applied to the measured cross-section and the associated systematic errors. A correction factor of 5% has been obtained for the largest energy bin and lower values for the other ones. The resulting p-air production cross-sections, $\sigma_{p\text{-}air}$, for the considered five primary energy values, are shown in Fig. 4. They are consistent with previous ARGO-YBJ results that were obtained without using the strip information [20] or with a fraction of the detector only [21]. Moreover the low energy threshold of ARGO-YBJ (with respect to other EAS experiments) allows a direct comparison with the values given by other techniques, showing a good agreement. This is particularly important since the systematics of the measurement techniques are completely different [11].

The p–p total cross-section σ_{p-p} can be inferred from the measured p-air production cross-section $\sigma_{p\text{-}air}$ as discussed in several papers [13]. In our energy range models differ by less than 10%, this being considered a separate further contribution to the systematic error on σ_{p-p}. The results, for the five energy bins, are summarized in Fig. 5. As can be seen, ARGO-YBJ data lie in an energy region not yet reached by p–p colliders (and still unexplored by $p-\overline{p}$ experiments [23]), favouring the asymptotic $\ln^2(s)$ increase of total hadronic cross-sections as obtained in [24] from a global analysis of accelerator data.

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