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PROCEEDINGS
SUPPLEMENTS

The Proton Attenuation Length and the p-air Inelastic Cross Section at $\sqrt{s} \sim 2$ TeV from EAS-TOP

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The attenuation length of proton primaries and the proton-air inelastic cross section are studied at energies $E_0 \approx 10^{15}$ eV by using the EAS-TOP array data. Proton initiated Extensive Air Showers, in the energy range $(2 \div 4)\,10^{15}$ eV and near maximum development, are selected from their $N_\mu(E_\mu > 1\,\mathrm{GeV})$ and N_e sizes.
The experimental attenuation length $\Lambda_{\rm obs}$ is compared with those obtained from simulations, including the full detector response, based on different interaction models (HDPM, VENUS, DPMJET, QGSJET and SIBYLL) in the frame of CORSIKA code. The proton-air inelastic cross section is also inferred by using the factor $k = \Lambda^{\rm sim}_{\rm obs}/\lambda^{\rm sim}_{p-\rm air}$ obtained from each interaction model.

1. Introduction

UHE cosmic rays provide the possibility to measure general features of p-air (p-N) interactions at energies well beyond fixed target experiments and comparable with collider energies ($p\bar{p}$). The attenuation length ($\Lambda_{\rm obs}$) of primary protons is one of such main observables. Different techniques [1,2] have been used to get such information from cosmic ray data. The present method [1,3] is based on the selection of showers with given primary energy ($E_1 < E_0 < E_2$) from the detected muon number $N_\mu(E_0, r, E_\mu > 1\,\mathrm{GeV})$. Primary proton showers near maximum development are selected requiring large electron shower sizes (N_e). The attenuation length of p-primaries in atmosphere ($\Lambda_{\rm obs}$) is measured from the frequency attenuation rate of such showers at different zenith angles.

Extensive Air Showers have been simulated (including full detectors' responses) in the frame of CORSIKA code [4] using different hadronic interaction and propagation models (HDPM [5], VENUS [6], DPMJET [7], QGSJET [8] and SIBYLL [9]). Interaction models can thus be verified comparing experimental and simulated data. Furthermore, the factor $k = \Lambda^{\rm sim}_{\rm obs}/\lambda^{\rm sim}_{p-\rm air}$ is calculated for each interaction model and $\lambda_{p-\rm air} = \Lambda_{\rm obs}/k$ (*i.e.* $\sigma^{p-\rm air}_{\rm in}$) is inferred.

2. The detector and the simulation

EAS-TOP [10,11] is an Extensive Air Shower array located at Campo Imperatore (National Gran Sasso Laboratories, 2005 m a.s.l., $x_0 = 820\,\mathrm{g/cm^2}$). The e.m. detector is made of 35 scintillator modules, 10 m^2 each, distributed over an area of $\approx 10^5\,\mathrm{m}^2$. The EAS arrival direction is obtained using the time of flight technique. From the fit to NKG lateral distribution function, shower size (N_e) and core location (x_c, y_c) are derived. For $N_e \geq 2.10^5$ the shower size, core location and arrival direction are measured with accuracies, respectively: $\frac{\sigma(N_e)}{N_e} \approx 10\%$, $\sigma_r \approx 5$ m

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Table 2
Measured and simulated attenuation lengths $\Lambda_{obs}(g/cm^2)$. Different accuracies in the simulations are due to different statistics.

$\log N_e^i$	6.0	6.1	6.2
Exp. Data	75 ± 5	76 ± 6	75 ± 7
He correction	96 ± 6	93 ± 7	86 ± 8
HDPM	90 ± 9	83 ± 9	80 ± 10
VENUS	78 ± 7	72 ± 7	75 ± 10
DPMJET	71 ± 6	66 ± 6	66 ± 7
QGSJET	74 ± 6	69 ± 6	65 ± 7
SIBYLL	105 ± 12	89 ± 10	71 ± 8

Table 1
Fraction of vertical events (%) selected with different cuts (N_e^i) in the given interval of N_μ.

$\log N_e^i$	6.0	6.1	6.2
Exp.	7.3	3.3	1.4
HDPM	38.0	19.8	9.5
VENUS	18.2	9.0	3.8
DPMJET	22.8	12.8	6.1
QGSJET	27.0	15.7	8.1
SIBYLL	52.0	37.3	24.6

and $\sigma_\theta \approx 0.5°$.

The muon number N_μ is obtained by means of a tracking detector (144 m^2 area) made of 9 double layers of streamer tubes interleaved by 9 layers of iron absorbers (13 cm thick). The readout is performed on orthogonal x (wires) and y (strips) views. A muon track is defined by the alignment of at least 6 hits in different layers of the muon tracking system. The energy threshold for vertical incidence is ≈ 1 GeV. The muon number is correctly measured up to $N_\mu \approx 30$.

Proton initiated EAS have been simulated, by means of the CORSIKA code, taking into account interactions of particles (muons and electrons) with the detectors. The GEANT code and NKG formalism have been used to describe the muon and electromagnetic detectors respectively. Experimental fluctuations in individual scintillator modules, trigger generation and event reconstruction have been included.

The selection on primary energy (E_0) is made using the detected muon number $N_\mu(E_0, r, E_\mu > 1\,\text{GeV})$. The relationship between these quantities, established with the quoted simulation, is:

$$N_\mu = 1.34 \times 10^{-3} \times \cos^{1.97}\theta \times E_0^{0.9} \times f(r), \quad (1)$$

where $f(r)$ is the muon lateral distribution:

$$f(r) = r^{-0.75} \times (1 + r/320.)^{-2.5}. \quad (2)$$

Expression (1) holds for energies $10^6\,\text{GeV} < E_0 < 10^7$ GeV, core distance $50\,\text{m} < r < 150\,\text{m}$ and zenith angle $\theta < 45°$.

Table 3
$k = \Lambda_{obs}^{sim}/\lambda_{p-air}^{sim}$ for different N_e^i cuts and models.

$\log N_e^i$	6.0	6.1	6.2
HDPM	$1.30 \pm .13$	$1.20 \pm .13$	$1.16 \pm .15$
VENUS	$1.19 \pm .11$	$1.08 \pm .11$	$1.14 \pm .15$
DPMJET	$1.18 \pm .10$	$1.11 \pm .10$	$1.11 \pm .12$
QGSJET	$1.27 \pm .11$	$1.18 \pm .11$	$1.11 \pm .12$
SIBYLL	$1.63 \pm .18$	$1.39 \pm .16$	$1.11 \pm .12$

3. Analysis and results

Events with primary energy $2.10^6\,\text{GeV} < E_0 < 4.10^6$ GeV are selected using expression (1), given their core distance (r), zenith angle (θ) and detected muon number (N_μ). Events with core distance $r < 50\,\text{m}$ or $r > 150\,\text{m}$ are discarded to avoid saturation problems and large fluctuations due to small muon numbers.

In order to select proton initiated showers near maximum development, events belonging to the uppermost few percent of the simulated shower sizes distribution are used. Three cuts ($\log N_e^i = 6.0 \div 6.2$) are performed, to obtain information on the stability of the measurement. The corresponding percentage of selected vertical events

Table 4
Values of σ_{in}^{p-air}(mb) inferred from experimental data using k factors derived from different interaction models. Accounting for He contamination, all values should be divided by the α correction factor corresponding to each N_e^i cut.

$\log N_e^i$	6.0	6.1	6.2
HDPM	419 ± 50	381 ± 52	375 ± 61
VENUS	380 ± 42	343 ± 44	369 ± 60
DPMJET	380 ± 40	350 ± 42	358 ± 52
QGSJET	407 ± 44	373 ± 46	358 ± 52
SIBYLL	524 ± 69	440 ± 60	358 ± 53

is shown in Table 1. The fraction of experimental events, also given, is lower than the simulated ones, because experimental data include heavier primary nuclei which produce, for fixed muon number, smaller electron size showers.

The frequency attenuation length in the atmosphere Λ_{obs} is obtained by fitting the rate of selected events with the following expression:

$$f(\theta) = \Gamma(\theta) f(0) \exp[-x_0(\sec\theta - 1)/\Lambda_{obs}], \qquad (3)$$

where $\Gamma(\theta)$ is the calculated acceptance.

Possible helium contamination is estimated using HDPM. Superimposing a flux of the same intensity as the proton one, a correction factor α has been found such as $\Lambda_{obs}(p) = \alpha \times \Lambda_{obs}(p\text{+He})$ (with α=1.28,1.22,1.14 for $\log N_e^i = 6.0, 6.1, 6.2$).

Experimental values are stable for different cuts as shown in Table 2. The Λ_{obs} value obtained ($\Lambda_{obs} = 75 \pm 7$ g/cm^2 for $\log N_e^i = 6.2$, possibly underestimated of about 10% in case of heavier nuclei contamination) is in better agreement with models predicting longer absorption lengths such as HDPM and VENUS.

The simulated attenuation lengths Λ_{obs}^{sim}, compared to the interaction mean free path λ_{p-air}^{sim}, provide the factor $k = \Lambda_{obs}^{sim}/\lambda_{p-air}^{sim}$. This factor includes shower fluctuations, detectors' response and some features of the interaction model. The values of k are similar and stable for all considered models and ≈ 1.1 for N_e^i cut high enough to select p-showers near maximum (*i.e.* $N_e = 10^{6.1} - 10^{6.2}$, see Table 3).

From $\lambda_{p-air} = \Lambda_{obs}/k$ the measurement of λ_{p-air} and consequently of $\sigma_{in}^{p-air}(\text{mb}) = 2.41 \times 10^4/\lambda_{p-air}$ is obtained. Results are reported in Table 4, where the $\log N_e^i = 6.2$ cut column should be considered, due to the convergence of k values and smaller contamination of heavier nuclei. Differences between σ_{in}^{p-air} values derived from each interaction model are well inside the present statistical uncertainties (still large, but mainly due to the statistics of the simulation). A helium contamination (considering equal p and He fluxes at $E_0 \approx 10^{15}$ eV) would result in a reduction of σ_{in}^{p-air} values by a factor ≈ 1.1. The obtained range for $\sigma_{in}^{p-air} = (300 \div 400)$ mb is anyway lower than previously reported in literature [1,2]. This is a consequence of the smaller k values obtained, in the present work, from full event simulations with all the quoted high energy hadron interaction models.

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