Air shower fluctuations and the measurement of the proton-air cross section

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Abstract

We explore the influence of fluctuations in the extensive air shower (EAS) development on the possibility to determine the proton-air cross section at high energy. This contribution concentrates on the two classical methods of obtaining the cross section in EAS experiments, (i) the measurement of the attenuation of the rate of showers with fixed muon and electron sizes with zenith angle, namely the constant intensity cut method, and (ii) the measurement of the distribution of the depth of maximum. We demonstrate that, depending on the selection method, shower fluctuations can strongly influence the characteristics of the selected showers in method (i). Method (ii) is subject to model dependence.

1. Introduction

Measuring extensive air showers is currently the only way to study the cosmic ray spectrum at energies above 10^{14} eV, as well as the properties of hadronic interactions at $\sqrt{s}$ above 1.8 TeV. EAS are detected with air shower arrays which usually measure electron and muon densities and derive the total number of electrons N_e and muons N_μ at the detector level. At energies $E \geq 10^{17}$ eV the shower development can also be directly observed by measuring the fluorescence light from atmospheric nitrogen, induced by the ionization of the charged shower particles. These experiments can determine the depth at which the number of charged particles reaches its maximum value ($X_{\max}$) in a shower.

Here we study the influence of fluctuations in shower development on the possibility to determine the proton-air cross section in EAS experiments by two different methods (see (i) and (ii) in the abstract).

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2. The constant N_e-N_μ method

The determination of the inelastic p-air cross section from ground array data is performed by measuring the attenuation with zenith angle θ of the rate of showers having the same energy. It is assumed that N_μ gives a good estimate of the primary energy. Experimentally the fraction of proton-showers in the sample is enriched by selecting showers with large N_e within the same N_μ bin. Under the assumption of no shower fluctuations, selecting showers of fixed N_μ and N_e at different θ would guarantee that they have the same energy and that they only differ in the depth at which the first primary p-air interaction has occurred. This allows the measurement of the *absorption* length ($\Lambda_{\rm abs}$), which determines how the flux of the selected showers decreases with atmospheric depth, and is related to the inelastic p-air cross section. The absorption length is determined from the ratio of the frequency (f) of showers falling in a given (N_μ, N_e) bin measured at two zenith angles (θ_1 and θ_2):

$$R(\theta_1,\theta_2) = \frac{f(N_\mu,N_e,\theta_1)}{f(N_\mu,N_e,\theta_2)} = \exp\left[-\frac{X_{\rm v}}{\Lambda_{\rm abs}}(\sec\theta_1 - \sec\theta_2)\right], \qquad (1)$$

where $X_{\rm v}$ is the vertical depth of the detector.

In general, the primary cosmic ray flux consists of nuclei of a variety of mass numbers. Here we simplify the problem with the assumption that all primary particles are protons. We simulated 500,000 proton-induced showers at several zenith angles using the hybrid code described in [1]. Shower energies were drawn from an E^{-3} differential spectrum in the energy range between 10^{16} and 10^{18} eV and both SIBYLL 2.1 [4] and QGSjet98 [6] were used as hadronic interaction models. The detector induced fluctuations in $\log_{10} N_\mu$ ($\log_{10} N_e$) were implemented by Gaussian resolution functions of widths 0.1 (0.05), in order to match the errors reported by the Akeno group [5]. The detector is at Akeno depth $X_{\rm v} = 920$ g/cm^2.

We apply the constant $N_e - N_\mu$ method by first selecting showers which have $\log_{10} N_\mu$ between 5.25 and 5.45 at observation level as done in the Akeno analysis [5]. Only muons above the energy threshold of the Akeno experiment $E_\mu > 1$ GeV $\times \sec\theta$ are considered. We then select showers with constant N_e within that N_μ bin. In Fig. 1a we show the frequency ratios (1) of the showers as a function of the selected N_e. The ratio depends strongly on the N_e bin used for shower selection. According to Eq. (1) it should be constant over a certain range in N_e for all different zenith angle combinations, which is only the case in Fig. 1a for $\log_{10} N_e > 7.4$ in both SIBYLL 2.1 and QGSjet98 models. For large N_e values we do not see a significant model dependence. The bin in N_e chosen by Akeno for the cross section analysis ($\log_{10} N_e$ between 6.8 and 7.0, marked by the vertical lines in Fig. 1a) is located in a region where the intensity ratios depend strongly on N_e. The figure suggests that zenith angle dependent bins in electron

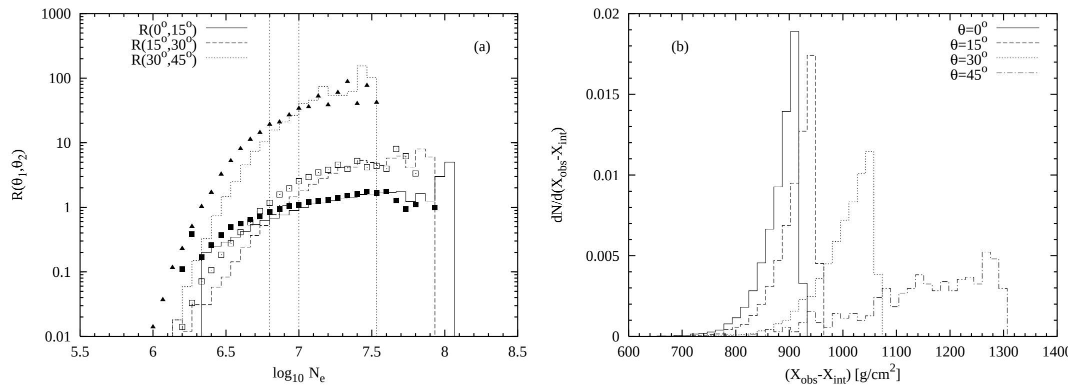

Fig. 1. Left panel: Ratios of number of proton-initiated showers having a muon number between $10^{5.25}$ and $10^{5.45}$ as a function of N_e. Histograms correspond to showers simulated using SIBYLL 2.1 and points show the results obtained with QGSjet98. Right panel: Distribution in $X_{\rm obs} - X_{\rm int}$ of the showers that fall in the $(\log_{10} N_\mu, \log_{10} N_e)$=(5.25-5.45,6.8-7.0) bin.

size should be used in order to get an angular-independent value of $\Lambda_{\rm abs}$.

The ultimate reason why the constant $N_e - N_\mu$ method does not work is that shower selection is dominated by the intrinsic fluctuations in shower development [2]. Our simulations indicate that an angle dependent selection bias is introduced by the constant $N_e - N_\mu$ method, so that instead of selecting showers which have developed through the same amount of matter between the first interaction $X_{\rm int}$ and observation level $X_{\rm obs}$, the selected showers have widely different "shower lengths" (defined as $X_{\rm obs} - X_{\rm int}$). Fig. 1b illustrates the distribution of shower lengths of showers with $(\log_{10} N_\mu, \log_{10} N_e)$=(5.25-5.45,6.8-7.0). The average values (σ) of the $X_{\rm obs} - X_{\rm int}$ distributions of the selected showers at $\theta = 0, 15, 30$ and 45 deg. are $\langle X_{\rm obs} - X_{\rm int}\rangle$ = 881.3 (35.7), 911.1 (37.6), 1002.0 (50.6) and 1152.9 (109.7) g cm^{-2} respectively.

3. The $X_{\rm max}$ method

The technique used to infer the p-air inelastic cross sections from the distribution of $X_{\rm max}$ at fixed shower energy exploits the correlation between the first interaction point and the depth of maximum [3]. In case of a perfect correlation one could use directly the slope (Λ_X) of the exponential tail of the $X_{\rm max}$ distribution of showers with large $X_{\rm max}$, to calculate the proton-air cross section. However, intrinsic shower fluctuations before the maximum is reached modify this correlation. A way to quantify this is to introduce a so-called k factor relating Λ_X and the p-air interaction length $\lambda_{\rm int}$ such that $\Lambda_X = k\lambda_{\rm int}$. The factor k depends on the pace of energy dissipation in the early stages of shower evolution, which in turn depends on the fluctuations of the features of the hadronic interactions, mainly inelasticity and multiplicity. The general rule is that large shower

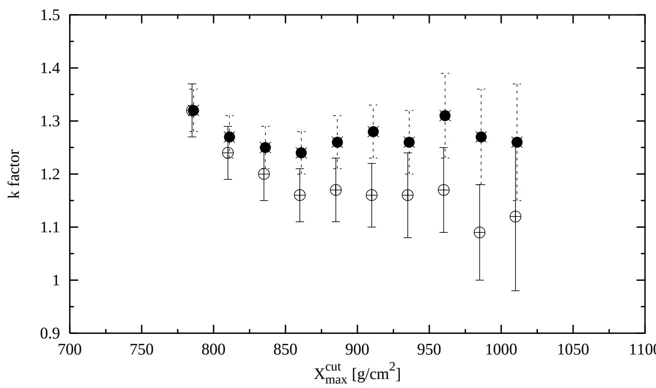

Fig. 2. Numerical values of the k factor as a function of $X_{\rm max}^{\rm cut}$ for proton showers at $E = 10^{19}$ eV. Filled (empty) symbols: Showers simulated with QGSjet (SIBYLL).

fluctuations lead to a larger k factor.

To explore the model dependence of the k factor we simulated proton-induced showers at $E = 10^{19}$ eV using SIBYLL 2.1 and QGSjet98 hadronic interaction models and calculated Λ_X from the predicted distribution of $X_{\rm max}$. Then we determine the k factor using $\lambda_{\rm int}$ provided by the model. In Fig. 2 we show the k factor as a function of $X_{\rm max}^{\rm cut}$, the minimal atmospheric depth above which we performed the fit to the tail of the $X_{\rm max}$ distribution. Firstly it can be seen that the k factor is larger for QGSjet due to the larger fluctuations in the inelasticity and multiplicity distributions predicted by this model as compared to SIBYLL. The dependence of k on $X_{\rm max}^{\rm cut}$ is also apparent, illustrating the fact that in general the $X_{\rm max}$ distribution is not exponential due to fluctuations in shower development. The determination of the dependence of k on $X_{\rm max}^{\rm cut}$ is needed for inferring the p-air cross section from real data. In this case, a cut in $X_{\rm max}$ is applied to avoid contaminating the sample with showers from heavy primaries. We are investigating this issue and the results will be published elsewhere.

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1. Alvarez-Muñiz J. *et al.* 2002, Phys. Rev. D 66, 033011
2. Alvarez-Muñiz J. *et al.* 2002, Phys. Rev. D 66, 123004
3. Baltrusaitis R.M. *et al.* 1984, Phys. Rev. Lett. 52, 1380
4. Engel R. *et al.* 1999, *Proc. of the 26th ICRC*, Vol. 1, p. 431; Engel R. *et al.* 2001, *Proc. of the 27th ICRC*, p. 415
5. Honda M. *et al.* 1993, Phys. Rev. Lett. 70, 525
6. Kalmykov N.N. *et al.* 1997, Nucl. Phys. B (Proc. Suppl.) 52B, 17