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Cosmic ray spectral deformation caused by energy determination errors

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Abstract

Using simulation methods, distortion effects on energy spectra caused by errors in the energy determination have been investigated. For cosmic ray proton spectra falling steeply with kinetic energy E as $E^{-2.7}$, significant effects appear. When magnetic spectrometers are used to determine the energy, the relative error increases linearly with the energy and distortions with a sinusoidal form appear starting at an energy that depends significantly on the error distribution but at an energy lower than that corresponding to the maximum detectable rigidity of the spectrometer. The effect should be taken into consideration when comparing data from different experiments, often having different error distributions.
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1. Introduction

A good knowledge of the steeply falling cosmic ray spectra of protons and nuclei is essential for, e.g., calculations of the interstellar production of antiprotons, positrons and photons. The calculation of the atmospheric production of neutrinos is also crucially dependent on a good knowledge of the flux of cosmic ray protons and nuclei. The determination of the energy of individual cosmic ray particles is subject to random statistical errors as well as systematic errors. When the statistical error is no longer small compared to the energy bin used, the steeply falling spectrum may cause deformations in the measured one. This feature is also true for spectra of photons and other charged particles.

It was observed early [1–5] that the steep form of the cosmic ray proton spectrum, where the particle flux decreases with kinetic energy E approximately as $E^{-2.7}$, together with a non-negligible error in the determination of the energy, causes a systematic overestimate of the energy.

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There are different ways of determining the particle energy in cosmic ray experiments. A magnetic spectrometer gives a relative momentum error $\Delta p/p$ for charged particles that is proportional to p. In some experiments the amount of Cherenkov light is used to determine the energy. In this case the relative energy $\Delta p/p$ increases as p^2, assuming that the error is determined from the number of observed Cherenkov photons. In air shower experiments, used for very high energies, the energy dependence of the error seems weaker than with other methods, and a logarithmic dependence has been used [5].

It is clear that when the energy resolution is much smaller than the bin width used to present data, the effect of the energy resolution can be neglected. However, many experiments tend to use as much as possible of accumulated data, including events with even 50% or worse energy resolution. In this case, there are significant effects on the observed spectrum from the resolution.

In this paper, we present results of a simulation study where effects of the energy resolution are studied for typically binned data, focussing on experiments using magnetic spectrometers and for energies up to about 1 TeV. Section 2 presents earlier work, Section 3 lays out the simulation procedure and the results are presented in Section 4. A summary is given in Section 5.

2. Earlier work

A detailed analysis of the effect of errors on high-energy air shower data was done by Edge et al. [5]. They conclude, from a simulation study assuming an error in the energy determination of 13% at 10^{17} eV increasing logarithmically to 200% at 10^{19} eV, that the spectrum at lower energies correctly describes the true spectrum whereas at energies closer to 10^{19} eV, the spectrum flattens significantly.

A method to correct measured energy spectra of cosmic ray nuclei in the range up to about 100 GeV/nucleon is discussed by Juliusson [6]. The measurements used the Cherenkov technique and the energy was estimated from the number of observed photons. The relative error in the momentum $\Delta p/p$ is in this case proportional to p^2. Juliusson concludes that measured fluxes must be increased by about 10% to as much as a factor of 2 for energy bins where the measured momentum is greater than about twice the Cherenkov threshold. The method was recently used [7] to correct measured cosmic ray fluxes of protons and helium nuclei in the range 30–150 GeV/nucleon.

Spectrum deformation effects caused by the energy resolution has been discussed for the BESS experiment [8], that utilizes a cylindrical magnetic spectrometer. In the BESS-98 experiment the deflection uncertainty distribution peaks at $5\,(\mathrm{TV})^{-1}$ corresponding to a maximum detectable rigidity MDR (Rigidity $R = pc/\mathrm{eZ}$, where p is the momentum, c the velocity of light and eZ the particle charge) of 200 GV [9]. From simulation studies, it is concluded that the proton spectrum deformation is small, below about 120 GeV, whereas at 230 GeV, the measured spectrum is 20% larger than the input $E^{-2.8}$ proton spectrum. For the improved BESS-TeV spectrometer [8], where the MDR is much higher, 1.3 TV, the deformation [10] for protons and helium nuclei (muons) was studied using an $E^{-2.7}$ and $E^{-3.2}$ input spectrum, respectively. The deformation was found to be less than 5% below 1 TV (400 GV). The larger effect for muons is caused by the larger spectrum index of -3.2 as compared to -2.7 for protons and helium nuclei.

Because of steeply falling fluxes, data are often presented as fluxes multiplied with $E^{2.75}$ or $E^{2.5}$ which makes the plots easier to show. When comparing data from different experiments, care must be taken to estimate the effects of the error of the energy determination, since errors assigned to each data point in these plots are usually based on the number of observed events neglecting the errors coming from the energy. Note that a 5% scale error in the energy determination changes the flux multiplied by $E^{2.75}$ by 14%. Detector inefficiencies, on the other hand, change fluxes linearly.

Finally, we mention that the problem of where to stick the data points in wide bins is discussed in a paper by Lafferty and Wyatt [11].

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