Limits on Antiprotons in Space from the Shadowing of Cosmic Rays by the Moon

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Abstract

An antiproton search in high energy cosmic rays is reported by observing the Moon shadow with the L3+C muon detector at CERN. An observation is made of a significant effect of the Earth magnetic field on the image of the Moon shadow. From the absence of any event deficit on the antimatter side, an upper limit on the amount of antiprotons in cosmic rays at TeV energies is estimated. The effect is used to demonstrate the absence of any significant systematic pointing error and to confirm the good angular resolution of the experiment.

1. Introduction

The effect of the Moon (or the Sun) on cosmic rays (CR) was first noted by Clark in 1957 [1]. As these bodies pass overhead they block particles, so their shadows in the CR flux must be visible by detectors on Earth. The observation may be used to check the angular resolution of the apparatus and to evaluate pointing errors. In 1990, a more challenging use of the Moon shadow effect has been proposed [2]. In the Earth magnetic field negatively charged primaries are deflected towards the west and positively charged primaries towards the east. If antiprotons are present at some level in the CR flux, there must exist an antimatter shadow on the opposite side of the Moon relative to the matter shadow. Alternatively, the non-observation of this "antishadow" allows to set a limit on the amount of antiprotons. Experimental data on antiprotons coming from balloon-borne experiments and recently from satellite experiments exist only below 40 GeV. Fig. 1, adapted from [3], shows a compilation of the $\overline{\mathrm{p}}/\mathrm{p}$ ratio as measured in different experiments together with expectations from models with basic assumptions on the origin and the propagation of antiprotons [4]. In this paper, we present a new search on CR antiprotons, using the L3+C muon spectrometer. A positive measurement would testify the existence of an anomaly in the antiproton flux as no standard source is known in this energy range.

The L3 detector [5], one of the four particle detectors installed on the Large Electron Positron Collider (LEP) at CERN, is located near Geneva (6.02°E, 46.25°N) at an altitude of 450 m and under 30 m of molasse. The muon spectrometer of L3 consists of a set of high precision drift chambers installed inside

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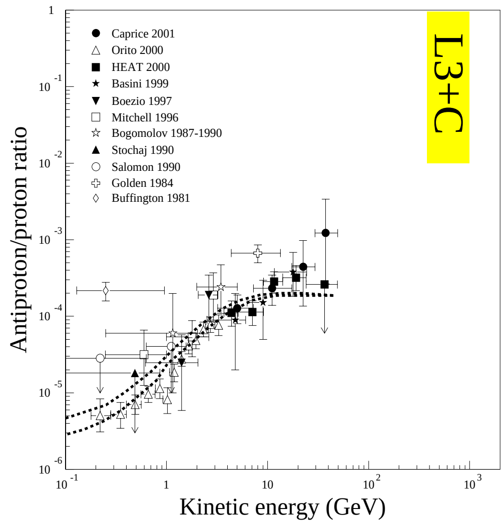

Fig. 1. Experimental data of $\overline{\mathrm{p}}/\mathrm{p}$ flux ratios versus the primary energy compared to model calculations. The dotted lines show the region of the theoretical expectations. The grey area at the right indicate the range investigated in this work.

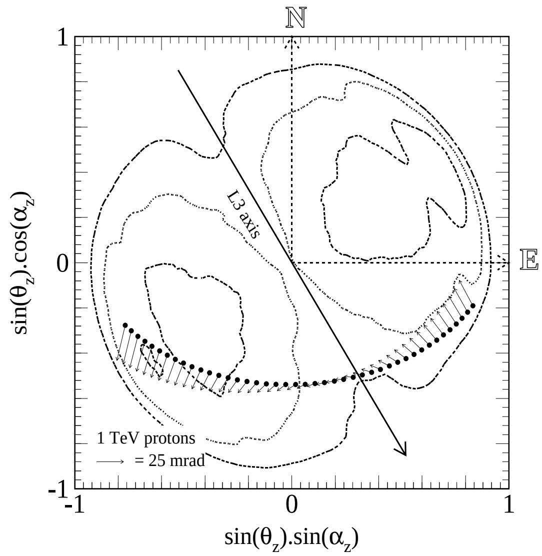

Fig. 2. The Moon through the L3+C acceptance. A Moon transit is indicated with dots. For each dot, the geomagnetic deflection (direction and amplitude) for a 1 TeV proton is indicated by an arrow.

a magnet with a volume of about 1000 m^3 and a magnetic field of 0.5 T. To fulfill the specific needs of a CR experiment and to make the running completely independent of L3 an additional timing detector and an independent trigger and read-out system were added to the L3 setup [6]. In addition, a scintillator air shower array of 54 m by 30 m has been installed at the surface. The geometrical acceptance of the detector amounted to some 200 m^{2}sr and the muon momentum threshold set by the overburden was 15 GeV. The detector started to be operational in July 1999 and a total of $1.2 \cdot 10^{10}$ muon triggers have been collected up to November 2000, corresponding to an effective live-time of 312 days.

2. The Moon Shadow Effect

As explained in section 1, the Moon shadow effect can be exploited to measure the ratio of antimatter to matter in cosmic rays, using ground-based experiment with Čerenkov detector, EAS arrays or muon track detectors. The first two methods are sensitive to the total energy of the primary E_0. The third method, characterized by the muon momentum threshold, is sensitive to the primary energy per nucleon E_0/A. The shadows from helium and heavier nuclei are almost at the same place. Therefore in the following, the Moon shadow will be considered as originating for 75% from protons and for 25% from helium nuclei.

The L3+C detector acceptance ranges from zenith angle $\theta_z = 0°$ to almost

60° and is given in Fig. 2. The apparent position of the Moon is computed with the SLALIB[7] package, taking into account parallax corrections, at any time. The effect of the Earth magnetic field has been simulated using the International Geomagnetic Reference Field (IGRF) model. Fig. 2 shows that both the direction and the amount of deflection undergone by primary particles vary with the position of the moon. It tends to blur the image of the Moon shadow. A new coordinate system, with axis parallel and orthogonal to the computed deflection has been defined to minimize this effect and will be referred to as the "deflection coordinate system".

3. The Moon Shadow Analysis

Muon tracks within 5° of the Moon and satisfying minimum quality cuts were considered, hereby selecting a total of $7.35 \cdot 10^5$ events. Studies to investigate the effect of the muon momentum threshold on the deficit lead to the definition of 2 samples, a "high energy (HE)" sample ($p_\mu > 100$ GeV) and a "low energy (LE)" sample (65 GeV $< p_\mu <$ 100 GeV). As a first step, the background has been subtracted from the data and a smoothing algorithm was applied (Fig. 3). The deficit is aligned along the horizontal axis as expected. Both the offset and the elongation due to the geomagnetic field are observed, with a more pronounced effect for low energy muons as expected. A parametrization was derived from the simulation mentioned in section 2, separately for the proton and helium deficits, as a function of the angular resolution. A maximum likelihood fit has been performed on the raw data, assuming 2 symmetric deficits for protons and antiprotons, and another deficit for helium:

$$\begin{aligned} g(x,y) &= \underbrace{u_x x + u_y y + u_z}_{\text{plane}} - \frac{N_{\text{miss}}}{1+r}[0.75\,\underbrace{f_1(x-x_0, y-y_0, \sigma)}_{\text{p deficit}} + \\ &\quad + 0.25\,\underbrace{f_2(x-x_0, y-y_0, \sigma)}_{\text{He deficit}} + \underbrace{r}_{\overline{\text{p}}\text{ ratio}}\,\underbrace{f_1(x_0-x, y_0-y, \sigma)}_{\overline{\text{p}}\text{ deficit}}], \end{aligned}$$

where parameters x_0 and y_0 describe a possible offset due to pointing errors.

The effective angular resolution and pointing error of the detector have been obtained from the observation of the matter deficit only. The antiproton ratio has not been included in this step. The extracted values of the angular resolution are $0.21°\,^{+0.04}_{-0.03}$ and $0.28°\,^{+0.07}_{-0.05}$ for HE and LE muon samples. The pointing error is deduced to be better than 0.1° in both cases.

To set a limit to a possible antiproton component, the number of missing events N_{miss} is supposed to be shared between protons, helium and antiprotons. The antiproton ratio is then added to the set of free parameters. The HE and LE results are combined to give the final measurement $r = -0.04\,^{+0.09}_{-0.08}$. Using the unified approach method [8], this leads to a 90% C.L. upper limit of 0.11 for the

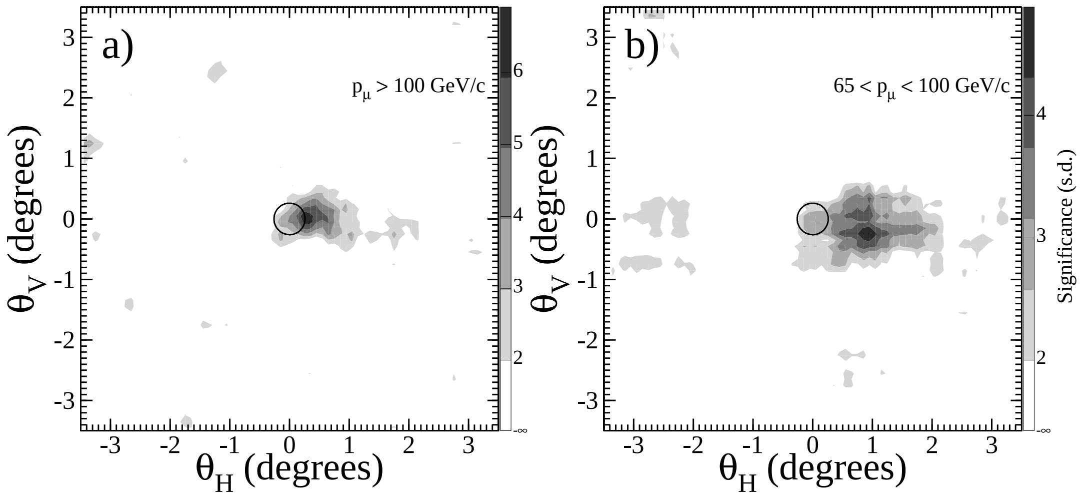

Fig. 3. Results obtained in the deflection system for: a) the HE sample, b) the LE sample. Smoothing techniques have been applied and the background has been subtracted. A circle indicates the real position of the Moon. The vertical grey scale shows the deficit significance in s.d. units.

antiproton to matter ratio. This corresponds to a $\overline{\mathrm{p}}/\mathrm{p}$ ratio of $r_{\overline{\mathrm{p}}/\mathrm{p}} = 0.15$. The total significance of the deficit is 10.4 *s.d* [9].

4. Conclusions

A significant effect due to the Earth magnetic field is observed. It confirms the good angular resolution and alignment of the detector. The observed significance of the Moon shadow effect is 10.4 *s.d.* A measurement of the $\overline{\mathrm{p}}/\mathrm{p}$ ratio yields an upper limit of 0.15 at 90% C.L. for the muon sample with $E_\mu \geq 65$ GeV. Only about 1/3 of the accumulated data has been used to extract this result. Consideration of the remaining events must lead to an improved value of this limit in the future.

5. References

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