Estimate of the pion contamination in the PAMELA antiproton measurements

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***Abstract*. PAMELA is a satellite-borne experiment designed and optimized to measure with high precision the antiproton and positron components of the cosmic radiation. The relative low abundance of antiparticles respect to the dominant proton flux makes necessary a deep understanding of any source of uncertainty which can affect the delicate spectrum measurement. In particular, the contamination from negatively charged pions originated in interactions of cosmic ray protons with the upper parts of the payload represents the main uncertainty in antiprotons measurements between about 1÷10 GeV, where the combined information from the several PAMELA subdetectors are not sufficient to allow an unequivocal pion-antiproton discrimination. The residual pion background has been evaluated by means of a dedicated simulation, developed to reproduce flight conditions with very high accuracy.**

***Keywords*: Antiprotons, cosmic rays, satellite experiments.**

I. Introduction

The PAMELA instrument [1], in orbit since June 15^{th} 2006 on board of the Resurs-DK1 satellite, has been conceived to study the antiparticle component of the cosmic radiation in a wide energy range with high precision and sensitivity. It is composed of a number of detectors which allow to determine particles identity and rigidity: a central magnetic spectrometer with microstrip tracker, an electromagnetic calorimeter, a time-of-flight system, a neutron detector and an anticoincidence shield.

Antiprotons constitute a very rare component of the cosmic radiation: between $1 \div 10\ GeV$ the antiproton-to-proton ratio is $< 10^{-4}$, while electrons result to be more than 2 order of magnitude more abundant than antiprotons. It is therefore fundamental an extensive study of any background affecting the measurement.

Another source of contamination, limited below $\sim 10\ GeV$, originates from secondary charged particles generated in the interaction of cosmic ray protons with the detectors and the mechanical structures of the upper parts of the apparatus, as schematized in figure 1, in particular with the pressurized container ($\sim 2\ mm$ aluminium window) housing PAMELA. Negatively charged pions represent the most significant background, resulting in a irreducible contamination above $1 \div 2\ GV$, where the velocity measurement from the ToF system combined with the information from the tracker are not sufficient to allow a clear unequivocal pion-antiproton discrimination.

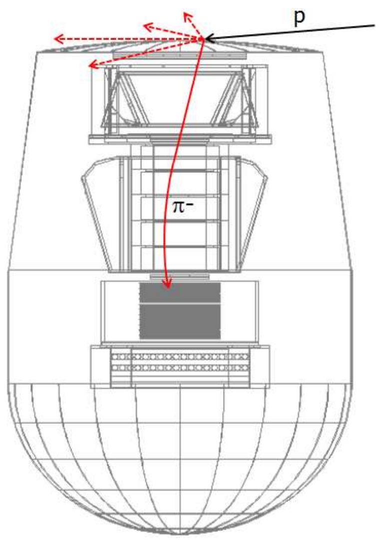


Fig. 1: An illustration of a cosmic ray proton interacting with the PAMELA pressurized container and originating a shower of secondary particles. Most of false antiproton candidates (mainly π^-) come from out-of-acceptance protons, which can produce events impossible to distinguish from real cosmic ray antiprotons.

A reasonable estimate of the contamination in the antiproton sample requires a reliable simulation of the cosmic rays interactions with the top of the experimental payload. An accurate description of PAMELA geometry and materials is fundamental to take into account the correct amount and content of matter crossed by incident particles in the apparatus, while a precise hadronic generator is crucial in order to reproduce as best as possible reaction dynamics and products multiplicities. Finally, very large statistics are needed, in consideration of the fact that possible false antiparticle candidates can be generated also by out-of-acceptance incident cosmic rays, as shown in figure 1: these events are even more difficult to be reconstructed and identified, only a portion of secondary products being detected.

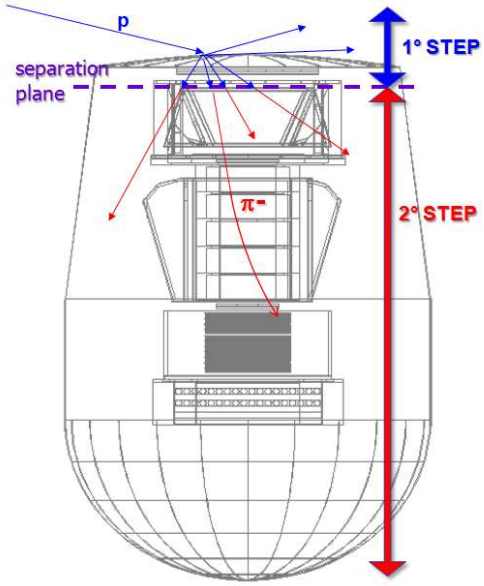


Fig. 2: A schematic drawing of the two-step simulation chain developed for the pion contamination study. Only events of interest were selected (first step) and then propagated in the rest of the apparatus (second step), allowing to minimize the large CPU time required to provide a reliable estimation of the background.

II. The simulation setup

The adopted approach [2] was based on a convenient two-step simulation according to the schematic representation shown in figure 2: the former stage, describing the proton generation and transport in the upper parts of PAMELA, discarded events not satisfying the requirements discussed below; the latter performed the transport only of events of interest in the rest of the apparatus. This resulted in a fast and accurate application which allowed to minimize the large CPU time required to provide a reliable estimation of the background.

The first step of the simulation was performed with an opportune application based on the FLUKA package [3], version 2006.3b-7. Since events interacting after the top scintillator plane (denoted with "$S1$") are easily identified with anticoincidences and by means of the segmentation of the ToF and the tracking system, only the upper components of the payload, where most of contaminating events are expected to be produced, were simulated: i) the top pressurized container (the "dome"); ii) the top scintillator plane; iii) the aluminium support structure which holds $S1$.

The pre-selection of events to be propagated in the second step of the chain was done by recording, out of the large incident proton sample, only events satisfying the following basic requirements: i) an inelastic reaction occurred; ii) at least a signal in $S1$ scintillators was recorded; iii) at least one of the produced secondary particles had the trajectory contained in the spectrometer acceptance. This allowed a remarkable reduction of the processing time, resulting in a very efficient pre-selecting application.

A virtual plane ("separation" plane), placed just below $S1$ table, divided the two steps of the simulation. When the pre-selection requirements were satisfied, all kinematic information (position, direction, energy, livetime, path, etc.) concerning secondary particles which reached such plane were saved and stored in a file to be used as input for the second step, together with all data related to the primary proton and to the signal induced in the $S1$ scintillators ($hits$). The successive part of the simulation chain, performing the transport of the pre-selected events below the separation plane (see figure 2), was realized with GPAMELA, the official montecarlo of the PAMELA experiment, based on the GEANT3.21 package [4].

The proton flux measured by PAMELA was used as input for the simulation. In order to get a realistic estimate of the pion contamination, geomagnetic modulation was also taken into account by considering measurements done in orbital regions characterized by different geomagnetic cut-off values: a mean PAMELA proton flux was obtained by weighting each flux by the live time spent by PAMELA in the corresponding cut-off interval, and associating to each generated event an opportune geomagnetic cut-off sampled from flight distributions. For completeness, the contribution from Helium nuclei, which constitute the most abundant cosmic ray species after protons, was evaluated too: in this case, the CAPRICE98 Helium flux [5] was used as input spectrum for the calculation, and DPMJET3 [6] was used as hadronic generator.

A mentioned before, the estimate of the pion spectrum requires the simulation of an incident proton flux generated in a large solid angle, including out-of-acceptance events. For this reason, a semi-spherical generation surface was implemented, placed just above the pressurized container, plus a cylindrical surface surrounding $S1$, in order to solve the problem with the minimum generation area and, consequently, to reduce the number of events to be generated.

III. Validation of the simulation

The simulation was first validated by means of a comparison with a sample of flight pions, opportunely selected in the low rigidities range where a good pion-antiproton discrimination is allowed using the combined information coming from the ToF and the tracker [7]. This permits also to normalize the calculated spectrum if differences are observed with flight data.

The simulated pion spectrum between $0.4 \div 1$ GV is shown in figure 3, where the calculated contributions from protons and Helium nuclei interactions is compared the pion spectrum measured by PAMELA. Results appear very satisfactory: the good agreement makes unnecessary any correction to normalize data. Helium nuclei contribution resulted to be negligible.

Simulated data have been further validated by comparing the fraction of surviving events after the application

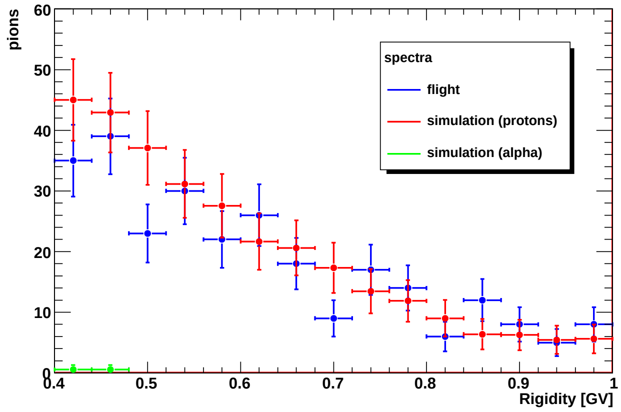
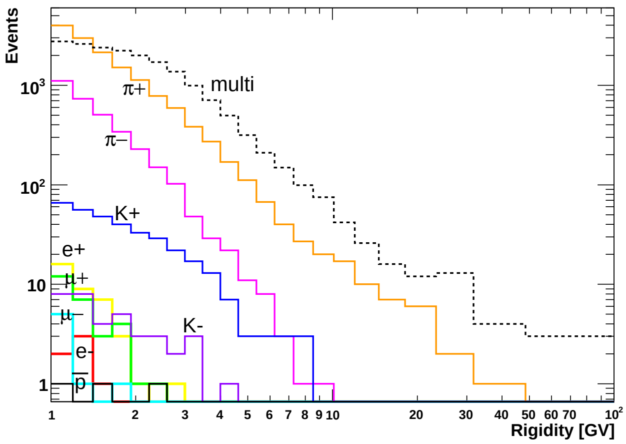
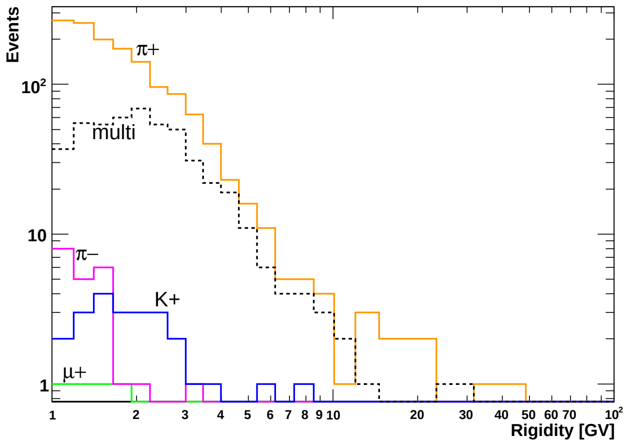


Fig. 3: Comparison between pions selected from flight data (blue) and simulated pions from protons (red) and Helium nuclei (green) interactions in the upper parts of the apparatus.



(a)



(b)

Fig. 4: The rigidity distribution of locally produced events between 1 and 100 GV, obtained after having applied the minimal track selection cuts (a) and all cuts involved used in the antiproton selection (b). For completeness, also positively charged particles (hence excluded from the antiproton analysis) are reported, including events (labeled as "multi") with more than a charged particle inside the tracker acceptance which were reconstructed as single track positively charged events. Shown statistics correspond to more than 4 years of data taking.

of each cut implemented in the antiproton flight analysis. Finally, a Kolmogorov-Smirnoff test was also performed to check the compatibility with the sample of antiproton candidates in each rigidity interval. All methods proved the reliability of the simulation, which was found to reproduce very well flight conditions.

IV. Results

A very large amount of montecarlo data was produced: about $3.5 \cdot 10^{11}$ protons and $3.6 \cdot 10^{10}$ Helium nuclei were generated, corresponding respectively to $\sim$ 7 and $\sim$ 3 years of data taking.

Selection criteria developed for the antiproton analysis were applied to the simulated sample in order to calculate the residual background. The calculated rigidity distribution of locally produced secondary particles between 1 and 100 GV is reported in figure 4: simulated samples obtained respectively after the minimal track selection (figure 4a) and after having applied all cuts of the $\bar{p}$ analysis (figure 4b) are shown for a comparison.

Also positively charged particles (hence excluded from the $\bar{p}$ selection) are reported for completeness. The main component is constituted by pions, with a minor contribution from $K+$ and $\mu+$; the rest is made of events with more than a charged particle inside the tracker acceptance: they are typically protons, accompanied by one or more pions, which were reconstructed as a single track positively charged event. This category of events is labeled as "multi" in the figure. $\pi-$ constitute the only contribution in the negatively charged sample. Shown data refer to a limited sample of simulated data corresponding to more than 4 years of data taking, and include only events in which an hadronic reaction occurred in the upper part of the apparatus. No secondary particle from Helium nuclei was observed in the final sample.

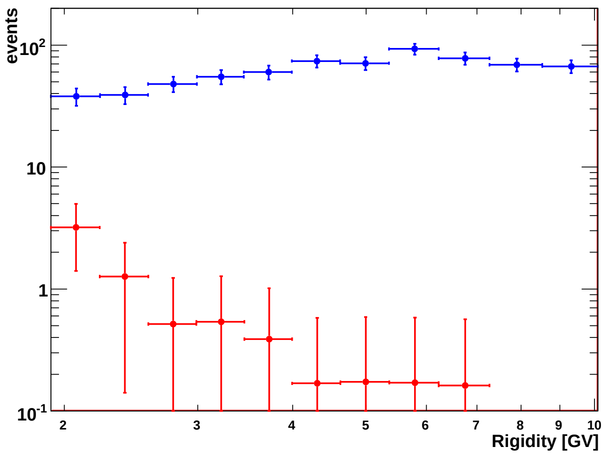


Fig. 5: Antiproton candidates above 2 GV and calculated π^- background. Simulation results ($\sim$ about 7 years of data taking) were normalized to the acquisition time of the flight sample, corresponding to about 500 days of data taking.

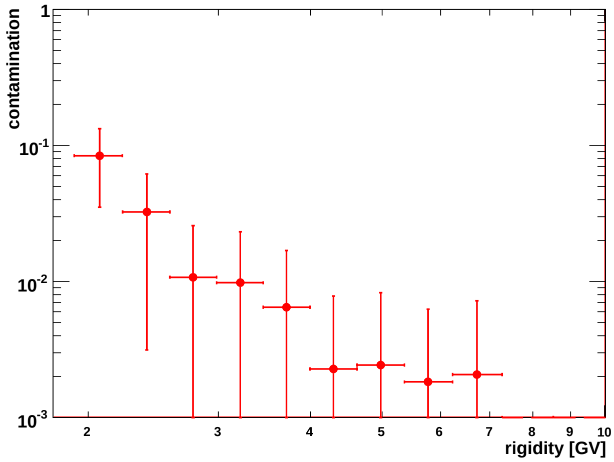


Fig. 6: The estimated pion contamination in the antiproton sample above $\sim 2\ GV$.

In figure 5 the simulated π^- spectrum is compared with flight $\bar{p}$ candidates above $\sim 2\ GV$. Simulation results were normalized to the acquisition time of the flight sample, corresponding to about 500 days of data taking. The residual pion fraction was calculated to be $\sim 8\%$ in the first bin (see figure 6), while it is of the order of 1% at 3 GV and becomes negligible for higher rigidities.

Results of the simulation study were used to properly take into account the pion background in the antiproton flux measurements [8], and in the antiproton-to-proton ratio measurements recently published by the PAMELA collaboration [9]. Moreover, the same simulation setup has been used to provide an estimate of the contamination from secondary particles also in the proton and in the positron fraction analysis [10].

REFERENCES

[1] P. Picozza et al, Astroparticle Physics, 27, 296, 2007.

[2] A. Bruno, Ph.D. thesis, University of Bari, 2008.

[3] A. Fassò, A. Ferrari, J. Ranft and P. R. Sala, "FLUKA: Status and Prospective for Hadronic Applications", in Proceedings of the MonteCarlo 2000 Conference, Springer-Verlag, Berlin, 2001, pp. 955-960.

[4] The GEANT team, "GEANT - Dectector Description and Simulation Tool", The CERN computing center. CERN Program Library Long Writeup W5013.

[5] E. Mocchiutti *et al.*, "The Cosmic-Ray Proton and Helium Spectra measured with the CAPRICE98 balloon experiment", Astroparticle Physics, Vol 19/5 pp 583-604 (2003).

[6] S. Roesler, R. Engel and J. Ranft, "The Monte Carlo event generator DPMJET-III", in Proceedings of the MonteCarlo 2000 Conference, Springer-Verlag, Berlin, 2001, pp. 1033-1038.

[7] P. Hofverberg, Ph.D. thesis, Royal Institute of Technology, Stockholm, 2008.

[8] A. Bruno et al., "A new measurement of the cosmic ray antiproton spectrum between 80 MeV and 14 GeV", this conference, OG.1.1 384, 2009.

[9] The PAMELA Collaboration, "A new measurement of the antiproton-to-proton flux ratio up to 100 GeV in the cosmic radiation", Phys. Rev. Lett. 102, 051101, 2009 (arXiv:0810.4994v1 [astro-ph]).

[10] The PAMELA Collaboration, "Observation of an anomalous positron abundance in the cosmic radiation", Nature 458, 607-609, 2 April 2009 (arXiv: 0810.4995 [astro-ph]).