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Cosmic rays studies with the PAMELA space experiment

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Summary. — The instrument PAMELA, in orbit since June 15th, 2006 on board the Russian satellite Resurs DK1, is delivering to ground 16 Gigabytes of data per day. The apparatus is designed to study charged particles in the cosmic radiation, with a particular focus on antiparticles as a possible signature of dark matter annihilation in the galactic halo; the combination of a magnetic spectrometer and different detectors—indeed—allows antiparticles to be reliably identified from a large background of other charged particles. New results on the antiproton-to-proton and positron-to-all-electron ratios over a wide energy range (1–100 GeV) have been recently released by the PAMELA Collaboration, and will be summarized in this paper. While the antiproton-to-proton ratio does not show particular differences from an antiparticle standard secondary production, in the positron-to-all-electron ratio an enhancement is clearly seen at energies above 10 GeV. Possible interpretations of this effect will be briefly discussed.

PACS `95.55.Vj` – Neutrino, muon, pion, and other elementary particle detectors; cosmic ray detectors.
PACS `98.80.Cq` – Particle-theory and field-theory models of the early Universe (including cosmic pancakes, cosmic strings, chaotic phenomena, inflationary universe, etc.).
PACS `11.10.Kk` – Field theories in dimensions other than four.
PACS `12.60.Jv` – Supersymmetric models.

1. – Introduction

The study of antimatter and antiparticle content in cosmic rays is a unique tool to investigate several physics and astrophysical phenomena. The idea of performing cosmic antiprotons and positrons measurements to probe unconventional particle physics and astrophysics scenarios has a long history and moved the cosmologists for several decades. The first historical discovery of antiprotons on the top of the atmosphere dates back to the balloon-borne experiments performed by Robert Golden and Edward Bogomolov in 1979 [1, 2]. They measured a rate of antiprotons much higher than expected from interactions of cosmic rays with the interstellar matter. Many theoretical ideas were developed to interpret these results as an evidence of the existence of large domains of antimatter, of evaporation by the Hawking process of primordial black holes produced very early in the hot Big Bang in the quantum gravity era, of annihilation of exotic particles.

The search of antimatter is strictly connected with the baryon-antibaryon asymmetry in the Universe. If we postulate the existence of primordial antimatter, antihelium would be the most likely form to be detected in cosmic rays, likewise in matter primordial nucleosynthesis. In addition, the detection of antinuclei with $Z > 2$ in cosmic rays would provide direct evidence of the existence of antistellar nucleosyntesis. Moreover, several authors [3, 4] suggest that small bubbles with very high baryonic asymmetry could have been produced by the presence of stochastic or dynamical violation of CP.

New cosmological observations are giving us a coherent picture of a Universe dominated by dark matter and dark energy. There are increasingly convincing evidences that non-baryonic dark matter is the building block of all structures in the Universe. It is now well known that the energy budget of the Universe is shared among baryonic matter (4%), dark matter (23%) and dark energy (73%). The nature of the dark matter is still unknown. The favourite candidates for the non-baryonic component are neutral weakly interacting massive particles (WIMP's) with a mass in the range between 10's of GeV to TeV. They would naturally appear as one of the thermal leftovers from the early Universe and their presence is predicted in several classes of extension of the Standard Model of particle physics. The most studied WIMP is the *neutralino*, combination of supersymmetric partners of the neutral gauge bosons of the Standard Model. Neutralinos are Majorana fermions and will annihilate with each other in the halo, resulting in the symmetric production of particles and antiparticles, the latter providing an observable signature. Another interesting candidate, among the many proposed, is the Kaluza-Klein lightest particle in the Universal Extra Dimension framework.

The search and identification of such possible sources are some of the major challenges in cosmic rays studies. However, these contributions are mixed with a huge background produced in the interaction of cosmic rays with the interstellar matter (ISM), so that they will appear as a distortion of antiproton, positron and gamma energy spectra due to this secondary production. Many balloon-borne experiments followed the pioneer ones, performed principally by the WiZard, BESS and HEAT Collaborations. Although the first historical results were not confirmed later, the way for a wide research for primary antimatter and dark matter signals in the cosmic rays was open. In 1998, on board the Space Shuttle, the AMS-01 Collaboration performed the first antimatter experiment outside the atmosphere. In June 2006 the satellite experiment PAMELA was launched in orbit by a Soyuz-U rocket from the Bajkonur cosmodrome in Kazakhstan.

2. – Instrument description

PAMELA [5], a Payload for Matter-Antimatter Exploration and Light Nuclei Astrophysics, is an experiment conceived for searching antimatter and dark matter signals in space. It is conducted by an international collaboration constituted of several INFN Divisions and Italian Universities, three Russian institutions (MEPhI and FIAN Lebedev in Moscow and IOFFE in St. Petersburg), the University of Siegen in Germany and the Royal Technical Institute in Stockholm, Sweden. The mission is performed within the framework of the RIM (Russian Italian Missions) Program, that took the heritage of the WiZard program.

The scheme of the PAMELA instrument is shown in fig. 1. PAMELA is built around a 0.43 T permanent magnet spectrometer, equipped with six planes of double-sided silicon detectors, 300 μm thick each, that allows the sign, absolute value of charge and rigidity of traversing charged particles to be determined. The resolution in the bending side is 4 μm and the MDR is 800 GV. Spillover effects limit the upper detectable antiparticle momentum to 190 GeV/c and to 270 GeV/c for antiprotons and positrons, respectively.

The discrimination between the hadronic and electromagnetic components is assured by two detectors, an imaging calorimeter and a neutron counter. The calorimeter is composed of 44 ministrip silicon layers, 380 μm thick each, placed alternatively in x and y directions and interleaved with 22 tungsten planes, for a depth of 16.3 radiation lengths and 0.6 interaction lengths. Tests with e^- and p CERN beams for wide energy intervals, as precise MonteCarlo simulations, verified a separation capability of the order of 10^5 in the e^-/p ratio and an energy resolution for electrons of 5.5% in the interval between 10 and 300 GeV. The neutron detector is composed of 36 ^{3}He counters displaced in two planes and inserted in 1 cm thick polystyrene. It counts neutrons in the showers induced in the calorimeter by hadrons or electrons. The different number of neutrons produced

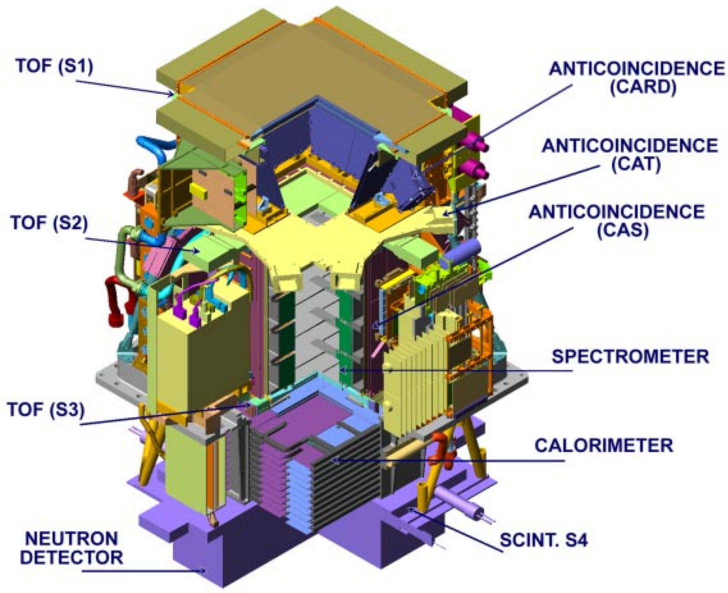

Fig. 1. – The PAMELA instrument: a schematic overview of the apparatus.

in hadronic or electromagnetic showers gives a supplementary tool in the discrimination between protons and positrons.

A set of 3 pairs of stripped plastic scintillators gives the trigger of the events and provides identification of particles coming from the bottom. Moreover, multiple $\mathrm{d}E/\mathrm{d}x$ measurements determine the module of the particle electrical charge. The spectrometer is surrounded by a plastic scintillator veto shield and the volume between the upper two time-of-flight planes is bounded by an additional plastic scintillator anticoincidence system. A plastic scintillator mounted beneath the calorimeter aids in the identification of high-energy electrons. The geometry factor of the instrument is $21.5\,\mathrm{cm}^2\mathrm{sr}$ and the total weight is 470 kg.

The apparatus, inserted in a pressurized container, was installed on board the Russian Resurs DK1 satellite (mass: 7.6 tons, height: 7.4 m), mainly devoted to Earth observation. The satellite was launched on June 15th 2006 and put in a quasi-polar (inclination 70°) low-earth elliptical orbit at an altitude ranging between 350 and 610 km.

The performance in flight of the PAMELA instrument enables searches for dark matter annihilation, antihelium (primordial antimatter) and new matter in the Universe (strangelets?). Other scientific objectives are the study of the cosmic ray production and propagation in our galaxy by precise measurements of the absolute fluxes of primary and secondary light nuclei, the monitoring of solar activity and cosmic rays solar modulation, the investigation of the interaction processes of cosmic rays with the Earth's magnetosphere, the search for high-energy electrons in order to discover local sources.

3. – Results and interpretation

Since July 2006 PAMELA instrument has been daily transmitting 16 Gigabytes of data by the satellite telemetry to the Ground Segment placed in Moscow at the NTsOMZ

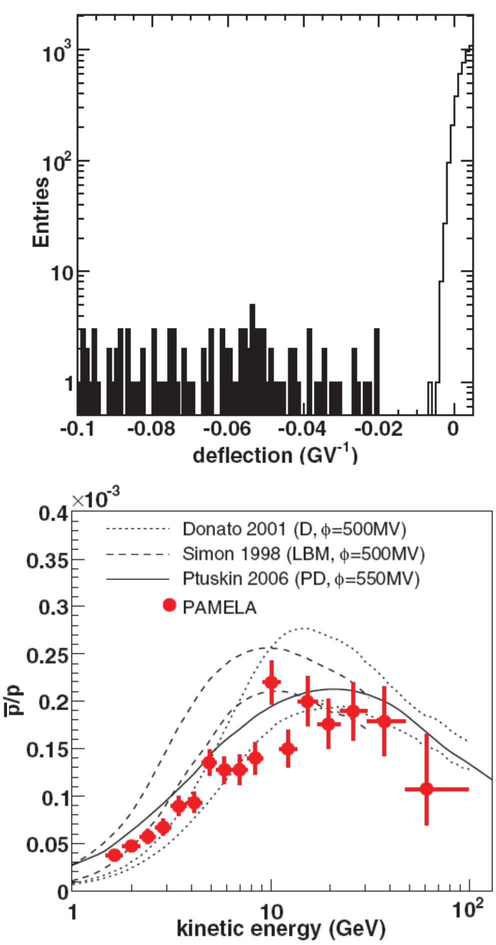

Fig. 2. – Top: the deflection reconstructed by the track fitting procedure for negatively and positively charged down-going particles. The shaded histogram corresponds to the selected antiprotons. Bottom: the antiproton-to-proton flux ratio published by PAMELA [6] compared with theoretical calculations for a pure secondary production of antiprotons [7-9].

institute. The results presented here are based on the data-set collected between July 2006 and February 2008. More than 10^9 triggers were accumulated during a total acquisition time of approximately 500 days.

Antiprotons identification was based on the determination of the rigidity by the spectrometer and the properties of the energy deposit and interaction topology in the calorimeter. The separation between negatively charged particles and spillover is shown in fig. 2, top. The calorimeter was used to reject electrons. The antiproton-to-proton flux ratio [6] measured by the PAMELA experiment is shown in fig. 2, bottom, compared with theoretical calculations assuming pure secondary production of antiprotons during the propagation of cosmic rays in the galaxy. The PAMELA data are in excellent agreement with recent results from other experiments, as shown in fig. 3. The ratio increases smoothly from about 2×10^{-5} at a kinetic energy of about 1 GeV and levels off

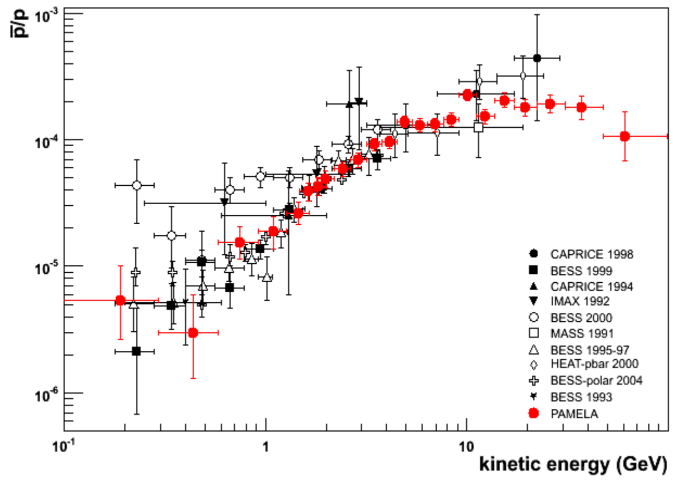

Fig. 3. – PAMELA antiproton-to-proton flux ratio compared with previous measurements [10-16].

at about 1×10^{-4} for energies above 10 GeV. The data do not present the features or structures expected from exotic sources, so they place strong limits to dark matter annihilation models. Moreover, they set tight constraints on parameters relevant for secondary production calculations, *e.g.*, the normalization and the index of the diffusion coefficient, the Alfven speed, and contribution of a hypothetical "fresh" local cosmic-ray component.

Positrons and electrons data need a very careful analysis, carried out by PAMELA using the most performing available instrumental and statistical tools, because the possibility of misidentification of protons as positrons. In fact, the proton-to-positron ratio increases from about 10^3 at 1 GeV to approximately 10^4 at 100 GeV. Particle identification was based on the matching between the momentum measured by the tracker and the total energy measured in the calorimeter, the starting point and the lateral and longitudinal profiles of the shower produced by particles in the PAMELA calorimeter, and the neutron detector response. This analysis technique has been tested at the proton and electron beams at CERN for different energies, by Monte Carlo simulations and by flight data.

The positron-to-all-electron ratio [17] measured by the PAMELA experiment is given in fig. 4. The calculation, shown in the same figure for pure secondary production of positrons during the propagation of cosmic rays in the Galaxy without reacceleration processes, proves that the positron fraction is expected to fall as a smooth function of increasing energy if secondary production dominates. In the figure PAMELA data are compared with other recent experimental data.

The data cover the energy range 1.5–100 GeV, with 151.672 electrons and 9.430 positrons identified. Two features are clearly visible. At low energies, below 5 GeV, the PAMELA results are systematically lower than data collected during the 1990's, while at high energies, above 10 GeV, they show a positron fraction increasing significantly with energy. Between 5 GeV and 10 GeV, the PAMELA positron fraction is compatible with other measurements.

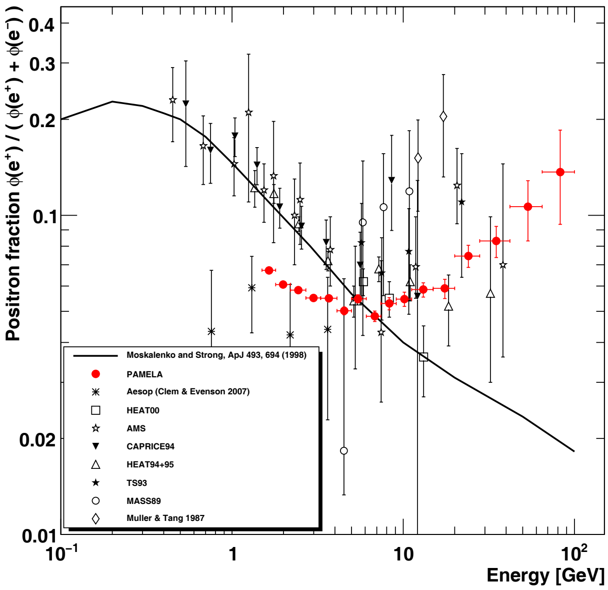

Fig. 4. – PAMELA positron fraction with a theoretical model. The solid line shows a calculation by Moskalenko and Strong [18] for pure secondary positron production during the propagation of cosmic rays in the galaxy. The positron fraction measured by the PAMELA experiment is compared with other recent experimental data [19-26].

This intriguing excess of positrons in the range 10–100 GeV has led to many speculations about its origin, as annihilation of dark matter, decaying dark matter, decaying of lightest superparticle dark matter, cosmic strings, young pulsars, a few nearby SNR.

A rise in the positron fraction at high energy has been postulated for the annihilation of dark matter particles in the galactic halo [27]. The most problematic theoretical challenge posed by the PAMELA results is the asymmetry between leptonic (positron fraction) and hadronic (antiproton-proton ratio), difficult to explain in the framework in which the neutralino is the dominant dark matter component (fig. 5). In this case suitable explanation requires a very high mass ($M = 10\,\mathrm{TeV}$, fig. 6) neutralino which is unlikely in the context of allow energy supersymmetry breaking model. Better explanations are obtained in terms of leptonic annihilation channel for a wide range of the WIMP mass (fig. 7). It is important to say, however, that all explanations in terms of dark matter annihilation request a boost factor for the annihilation standard rate ranging between 10^2 to 10^4.

Another explanation relates to a contribution from nearby and young pulsars, objects well known as particle accelerators [27]. Primary electrons are accelerated in the magnetosphere of pulsars in the polar cup and in the outer gap along the magnetic field lines emitting gamma-rays by synchrotron radiation, gammas that in the presence of pulsar gigantic magnetic field can evolve in positrons and electrons pairs. These, escaping into the interstellar medium, give a further contribution to the electron and positron components (as an example, fig. 8).

Main uncertainties in these calculations are connected to an incomplete knowledge of the primary cosmic-ray nuclei and primary electron spectra, of the interaction

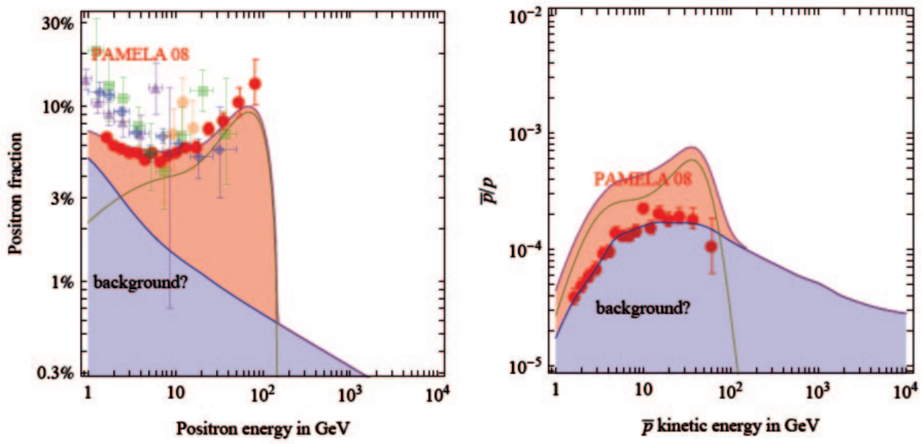

Fig. 5. – Example of fits of e^+ (left) and $\bar{p}$ (right) data, for a $M_{\rm WIMP} \approx 150\,{\rm GeV}$ and W^+W^- dominant annihilation channel [28].

cross-sections and the cosmic-ray propagation in the galaxy. Despite all these approximations, contributions from standard secondary production to explain this anomalous increasing of the ratio would demand high modifications in the current knowledge of the electrons, protons and helium spectra [30], although some papers report an explanation of this increasing in terms of few nearby SNR [31] or of secondary production taking place in the same region where cosmic rays are being accelerated [32]. However, to distinguish among the different hypotheses a better knowledge of the standard production of electrons and positrons is required as well of the mechanisms of their acceleration and transport in the galaxy. PAMELA is performing accurate measurements of the absolute fluxes of electrons, positrons, protons and light nuclei, that will constrain tightly the secondary production models.

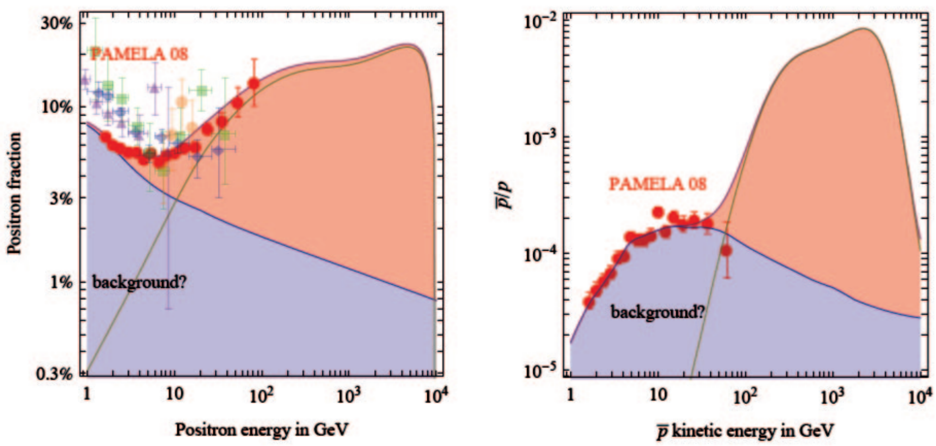

Fig. 6. – Example of fits of e^+ (left) and $\bar{p}$ (right) data, for a $M_{\rm WIMP} \approx 10\,{\rm TeV}$ and W^+W^- dominant annihilation channel [28].

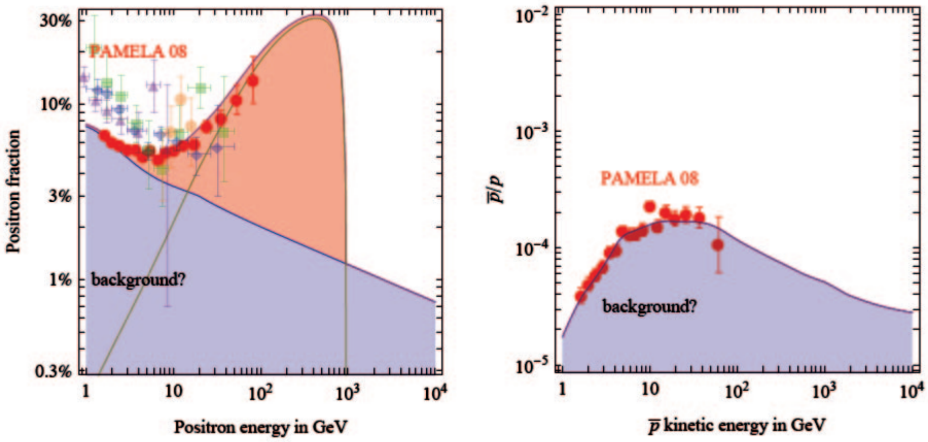

Fig. 7. – Examples of fits of e^+ (left) and $\bar{p}$ (right) data, for a $M_{\mathrm{WIMP}} \approx 1\,\mathrm{TeV}$ and $\mu^+\mu^-$ dominant annihilation channel [28].

Concerning the lower energy part of the spectrum, a disagreement between our data and the previous measurements is evident. This difference is interpreted as a consequence of time- and charge-dependent solar modulation effects. The energy spectra of cosmic rays are modified by the solar wind within the solar system, mainly at energy lower than 10 GeV. These solar modulation effects depend on the cosmic rays sign of charge and on the positive and negative phase of the Sun and it is due to gradient, curvature and drift effects. These mostly affect low-mass particles as positrons and electrons and are more important in the phase of low solar activity. The older results were obtained during the previous positive polarity of the solar cycle, when the mechanical rotation axis of the Sun and the Sun magnetic dipole had the same versus and positive charges

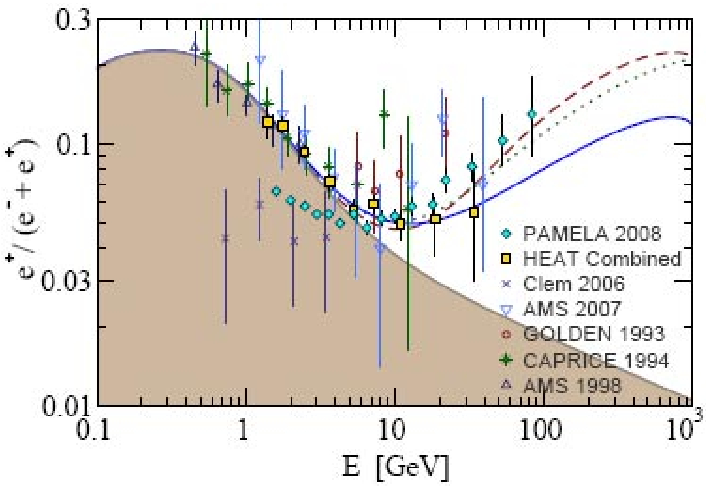

Fig. 8. – Contributions of e^- and e^+ from Geminga assuming different distance, age and energetics of the pulsar [29].

underwent a lower solar modulation. A balloon-borne experiment which flew in June 2006 has also observed a suppressed positron fraction at low energies, but with larger statistical uncertainties [26].

4. – Conclusions

Results from the analysis of the data collected and transmitted to ground from the PAMELA instrument in the first one and half year of operation show very interesting features in the positron-to-all-electron fraction. At energy above 10 GeV, an increase in the ratio, compared as expected from the standard secondary production, is generally interpreted in terms of positron primary sources, as dark matter annihilation or nearby pulsars contributions. Explanations in terms of nearby SNR or non-standard processes in the secondary positrons production are also reported. Solar modulation largely affects the low part of the spectrum, giving new information on the solar activity during the negative phase of the Sun. The antiproton-to-proton spectrum appears in agreement with the standard secondary production, in the collision between high-energy cosmic rays and interstellar matter.

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