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Muons. Another physics channel for AMS-02?

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Abstract

We want to bring the attention to the fact that muons in the 100-300 GeV energy range are identifiable in the AMS-02 detector. In this range, and with a simple set of cuts, we are able to obtain a muon acceptance of ≈ 0.03 m^2 sr, with rejection factors of order 10^3 against antiprotons and at least of order 10^5 against electrons. Very intense neutrino bursts traversing the Earth are a possible source of upward-going muons for AMS-02. Downward-going muons from space would signal the presence of unexpected interactions or decays producing muons within a distance of 2000 km from AMS. In particular, AMS-02 should be sensitive to unstable particles at the TeV scale with lifetimes up to 100 $B_\mu[\%]$ $\rho[\mathrm{MeV/cm^{-3}}]$ years, where ρ is their density and B_μ their branching ratio into $\mu^- + anything$ in the $100-300$ GeV muon energy range.

1 Introduction

The fact that the muon lifetime is $c\tau_\mu \approx 0.66$ km implies that muons with momentum $p_\mu \gtrsim 70$ GeV produced near the Earth surface or in the atmosphere can reach AMS-02 on the ISS (at 400 km from Earth surface) before decay. From the detection point of view, the TRD and ECAL subdetectors have the sensitivity to disentangle muons from protons and electrons, respectively. The TRD should be able to separate muons from protons with a rejection factor of order 10^3 in the $106 - 300$ GeV range, since muons and electrons produce similar transition radiation signals for boost factors above 1000. The sensitivity to antimuons (μ^+) will be poor, due to the huge proton background. On the other hand, rates of negative muons (μ^-) two to three orders of magnitude below the antiproton rates could be visible, assuming a perfect electron-muon separation in ECAL.

Let us note that a 100 GeV muon traveling a distance of 400 km in a magnetic field of 0.5 Gauss will have a sagitta of 3 km only. Assuming no new physics effects, and that the back of AMS-02 is pointing more or less to the center of the Earth, this small sagitta implies that high-energy upward-going muons should come from neutrino interactions in the atmosphere or close to the Earth surface. Downward-going muons should come from unexpected interactions or decays from a distance of less than 2000 km (for a 300 GeV muon) from AMS-02.

The first part of this Note presents a set of cuts to select muon events and to reject a maximum number of antiprotons and electrons. The last sections are devoted to a quantification of the AMS-02 potential and to a discussion of possible physics signals.

2 Muon selection

In order to select muons in the 100-300 GeV range the following cuts are applied:

- The event should have been triggered by TOF (3 out of 4 planes) or ECAL. No vertices from conversions are allowed and no more than one anticounter must be fired.
- We require at least one particle with a reconstructed track with a rigidity more negative than -50 GV, a reconstructed ECAL shower and a value of the TRD likelihood discriminating variable greater than 5. The separation power between muons and antiprotons in terms of this discriminating variable is shown in Figure 1.
- The particle should behave like a muon in ECAL. Therefore we require:
  - a distance between the extrapolated track from the tracker subdetector and the ECAL shower of less than 1.5 cm,
  - a span of the ECAL shower of more than 14 ECAL clusters,
  - less than 30 clusters in the ECAL shower,
  - and a deposited energy in ECAL smaller than 20% of the absolute value of the measured rigidity.

  The separation power between muons and electrons in terms of the energy/rigidity ratio is shown in Figure 2.

A total of 163 muons over a sample of 250000 muons in the 128-300 GeV energy range, generated on top of the AMS-02 detector, survive these cuts. Since the total generated acceptance is 47.78 m^2 sr, this implies an acceptance of (0.031 ± 0.002) m^2 sr.

Only three events out of 5 10^6 generated antiprotons at 256 GeV survive the previous cuts. This represents an acceptance of (3 ± 1) 10^{-5} m^2 sr, and a rejection factor of 10^3, essentially the same result that one would naively expect according to TRD identification capabilities.

Concerning the electron background, no events survive the cuts on samples of 10^7, 9 10^6 and 1.4 10^7 electrons generated at 128, 256 and 200-4000 GeV, respectively [1)]. Adding statistically the three samples, we can conclude that the electron acceptance is smaller than 10^{-6} m^2 sr at the 68% CL, which implies a rejection factor better than 2 10^4. In fact, we expect an even better performance, given the enormous separation power of some variables, like the energy/rigidity ratio shown in Figure 2. Our guess is that the rejection factor will most likely be better than 10^5.

As an additional exercise, we have checked the potential background from protons. One has to take into account that the applied rigidity cut (< -50 GeV) should lead to a negligible component compared to antiprotons. As expected, out of 6.3 10^7 generated protons in the usual 47.78 m^2 sr, none of them survived.

3 AMS-02 performance

All tests presented in the previous section suggest that AMS-02 should be able to measure muons with an acceptance of 0.03 m^2 sr and be sensitive to fluxes at least two orders of magnitude below the antiproton rate at 100 GeV. A realistic limit of sensitivity would therefore be a rate of order 10^{-7} $(\mathrm{m}^2\ \mathrm{s}\ \mathrm{sr}\ \mathrm{GeV})^{-1}$ in the 100-300 GeV energy range. In terms of number of events, this small rate is equivalent to 1 background-free muon measured by AMS in each 10 GeV bin.

4 Physics from upward-going muons into AMS-02

In a very much simplified view, AMS-02 will behave for this purpose as a EUSO-like detector [1], but with a different detection mechanism and a very limited acceptance for cosmic rays from Earth. Concerning the rate of upward-going muons from Earth, we should reasonably expect some muons from proton atmospheric cascades only if AMS-02 is aligned tangentially to the Earth sphere. If AMS-02 is pointing most of the time back to the center of the Earth, and in the absence of new physics effects, any upward-going muon in the 100-300 GeV range must come from the interaction of neutrinos in the atmosphere or close to the Earth surface. Detectors like Super-Kamiokande are only sensitive to neutrinos below 100 GeV [2]. AMS-02 therefore covers an interesting muon energy range, above 100 GeV, similar to that of high energy neutrino experiments like AMANDA [3]. Again, the AMS-02 acceptance is lower by several orders of magnitude, and the real question is if one can look for signals to which AMANDA is largely insensitive.

A first possibility is to search for extremely intense neutrino point sources. The present limit from the Northern hemisphere sky by AMANDA-II [3] for neutrino energies above 100 GeV is already around 10^{-7} $(\mathrm{m}^2\ \mathrm{s}\ \mathrm{GeV})^{-1}$, below the AMS-02 sensitivity. However, this limit does not exclude the presence of very intense high-energy neutrino sources in the Southern hemisphere, particularly those near the Galactic Center.

[1)] The sample of electrons in the 200-4000 GeV range is generated with a $\log E$ spectrum.

A second suggestive possibility is the search for exotic ultra high-energy particles in the TeV range with a low cross section in Earth, developing only hadronic-like cascades with subsequent decays into muons in the right energy range for AMS-02. The threshold of detectors like AMANDA for this kind of cascades is of several TeV. Some examples of very high energy particles of this kind exist in the literature. For instance, in models where the ultra-high energy cosmic ray problem is solved by the so called "top-down" scenarios, a significant flux of ultra-high energy neutralinos is predicted [4]. Although the estimated rates are somehow low in this particular scenario one should always be open to surprises.

5 Physics from downward-going muons into AMS-02

Observing downward-going muons in the 100-300 GeV range into AMS-02 would be a signal of an even more exotic scenario, and probably new physics. These muons should come from an "essentially empty" region of space around AMS-02, a sphere of radius 2000 km (for a 300 GeV muon).

Probably the most optimistic scenario would be the presence of exotic neutral pseudo-stable particles, like charmlets [5], having significantly long lifetimes and hopefully a non-negligible decay rate into muons. A particle of mass M and lifetime τ, presenting an average density ρ and a branching fraction into muons in the 100-300 GeV range of B_μ, would lead to a number of muons in three years, N_μ, of order:

$$N_\mu \approx 100 \, \frac{\rho[\mathrm{MeV/cm^3}] \; B_\mu[\%]}{M[\mathrm{TeV}] \; \tau[\mathrm{years}]} \; \mathrm{events} \tag{1}$$

For instance, a particle in the TeV range, with $\rho = 1$ MeV/cm^3 (a density three orders of magnitude below that of dark matter), and with a muon branching fraction of 1%, will still be detectable in AMS-02, provided that its lifetime is below 100 years or so.

We have also thought about other exotic, most likely negligible, possibilities:

- The moon surface will act as target of ultra high-energy neutrino interactions. Whenever the moon is facing AMS-02, we could observe the decays of ultra high-energy taus ($E \approx 10^{13}$ GeV) or pions ($E \approx 10^7$ GeV) into muons.

- A process leading to muons in the final state is dark matter annihilation. Unfortunately, the extremely low cross section and the considered volume prevents any observable rate, even in the presence of large boost factors.

- Another possibility would be muon pair production out of dark energy, but the current understanding of this exotic component in the Universe suggests a negligible rate of decay into ordinary matter [6].

- Charged cosmic rays can interact with each other. However their small density $<$ meV/cm^3 around AMS and their steep spectra should lead to a negligible production rate at the required energies.

- High-Z nuclei are expected to radiate muons [7]. However the small expected rates of high-Z ions and the high energy required to detect a muon imply a negligible rate.

- Violations of Lorentz invariance could provoke the stability of some particles (like taus, pions) above a given threshold energy [8]. After energy loss in the interstellar medium they could decay into muons of lower energy in the vicinity of AMS.

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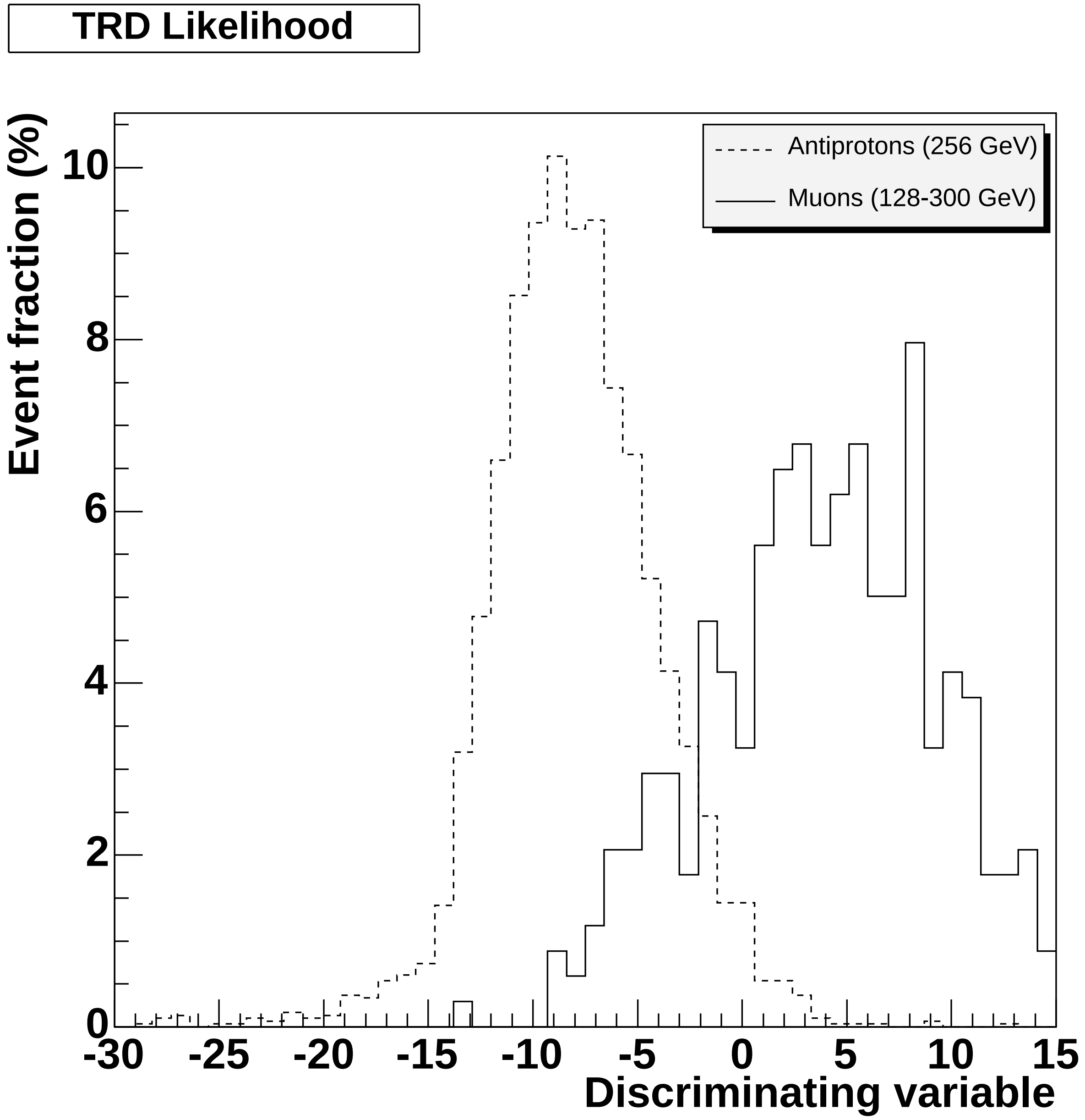

Figure 1: Separation between muons in the 128-300 GeV energy range and antiprotons at an energy of 256 GeV. The discriminating variable is the TRD likelihood of the selected particle. The solid histogram corresponds to muons, and the dashed one to antiprotons. All cuts but this one (likelihood variable > 5) have been applied.

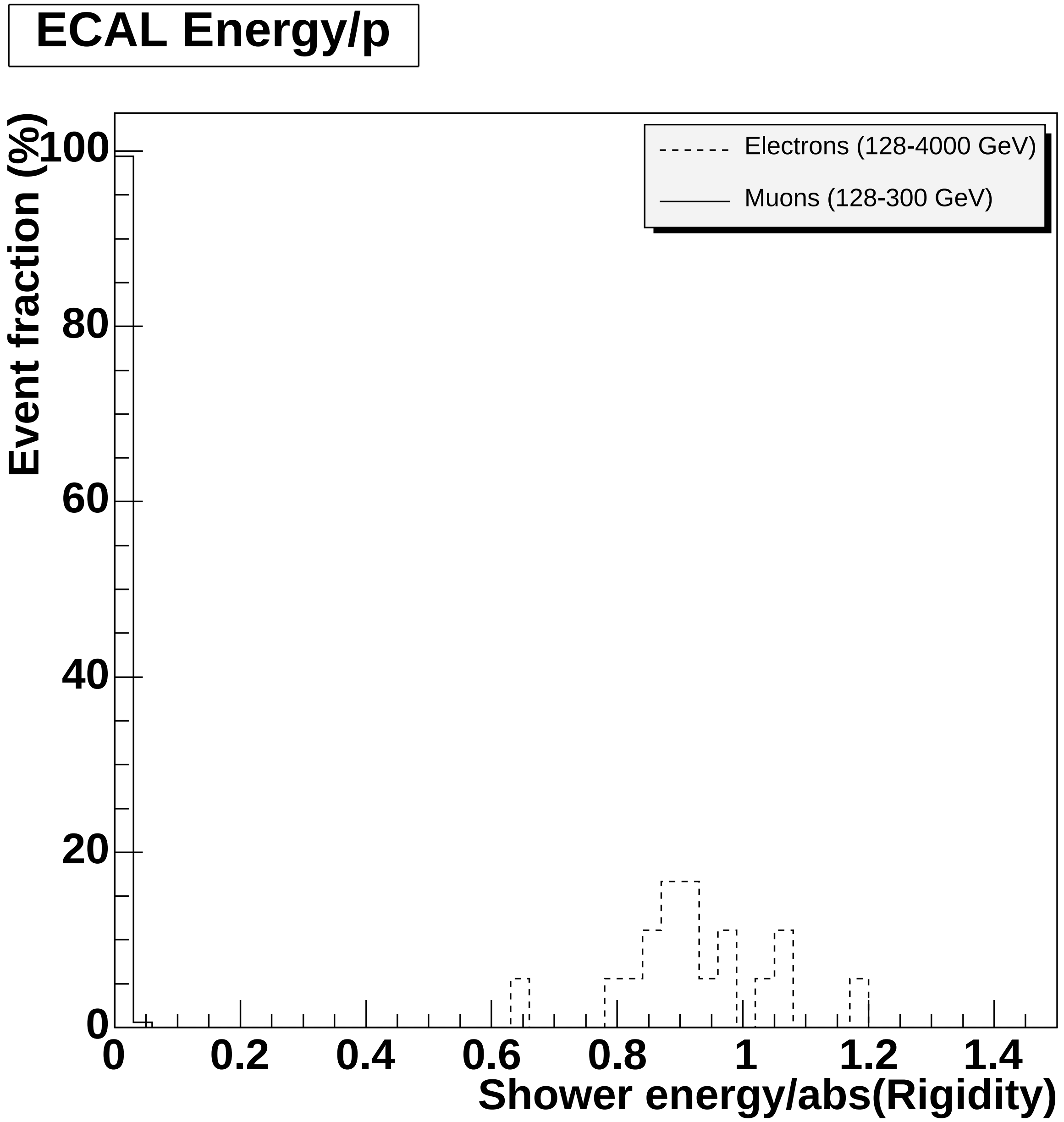

Figure 2: Separation between muons in the 128-300 GeV energy range and electrons in a similar energy interval (128 GeV and above). The discriminating variable is the ratio of the shower energy over the absolute value of the rigidity. The solid histogram correspond to muons, and the dashed one to electrons. All cuts but this one (ratio<0.2) have been applied.