Particle identification with the AMS-02 RICH detector: search for dark matter with antideuterons

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***Abstract*— The Alpha Magnetic Spectrometer (AMS), whose final version AMS-02 is to be installed on the International Space Station (ISS) for at least 3 years, is a detector designed to measure charged cosmic ray spectra with energies up to the TeV region and with high energy photon detection capability up to a few hundred GeV, using state-of-the art particle identification techniques. It is equipped with several subsystems, one of which is a proximity focusing Ring Imaging Čerenkov (RICH) detector equipped with a dual radiator (aerogel+NaF), a lateral conical mirror and a detection plane made of 680 photomultipliers and light guides, enabling precise measurements of particle electric charge and velocity (= 10 ^{3} and 10 ^{4} for Z = 1 and Z = 10 20, respectively) at kinetic energies of a few GeV/nucleon. Combining velocity measurements with data on particle rigidity from the AMS-02 Tracker (R=R 2% for R = 1 10 GV) it is possible to obtain a reliable measurement for particle mass. One of the main topics of the AMS-02 physics program is the search for indirect signatures of dark matter. Experimental data indicate that dark, non-baryonic matter of unknown composition is much more abundant than baryonic matter, accounting for a large fraction of the energy content of the Universe. Apart from antideuterons produced in cosmic-ray propagation, the annihilation of dark matter will produce additional antideuteron fluxes. Detailed Monte Carlo simulations of AMS-02 have been used to evaluate the detector's performance for mass separation, a key issue for D=p separation. Results of these studies are presented.**

I. THE AMS-02 EXPERIMENT

The Alpha Magnetic Spectrometer (AMS)[1], whose final version AMS-02 is to be installed on the International Space Station (ISS) for at least 3 years, is a detector designed to study the cosmic ray flux by direct detection of particles above the Earth's atmosphere using state-of-the-art particle identification techniques. AMS-02 is equipped with a superconducting magnet cooled by superfluid helium. The spectrometer is composed of several subdetectors: a Transition Radiation Detector (TRD), a Time-of-Flight (TOF) detector, a Silicon Tracker, Anticoincidence Counters (ACC), a Ring Imaging Čerenkov (RICH) detector and an Electromagnetic Calorimeter (ECAL). Fig. 1 shows a schematic view of the full AMS-02 detector. A preliminary version of the detector, AMS-01, was successfully flown aboard the US space shuttle Discovery in June 1998.

The main goals of the AMS-02 experiment are:

- A precise measurement of charged cosmic ray spectra in the rigidity region between 0.5 GV and 2 TV, and the detection of photons with energies up to a few hundred GeV;
- A search for heavy antinuclei (Z 2), which if discovered would signal the existence of cosmological antimatter;
- A search for dark matter constituents by examining possible signatures of their presence in the cosmic ray spectrum.

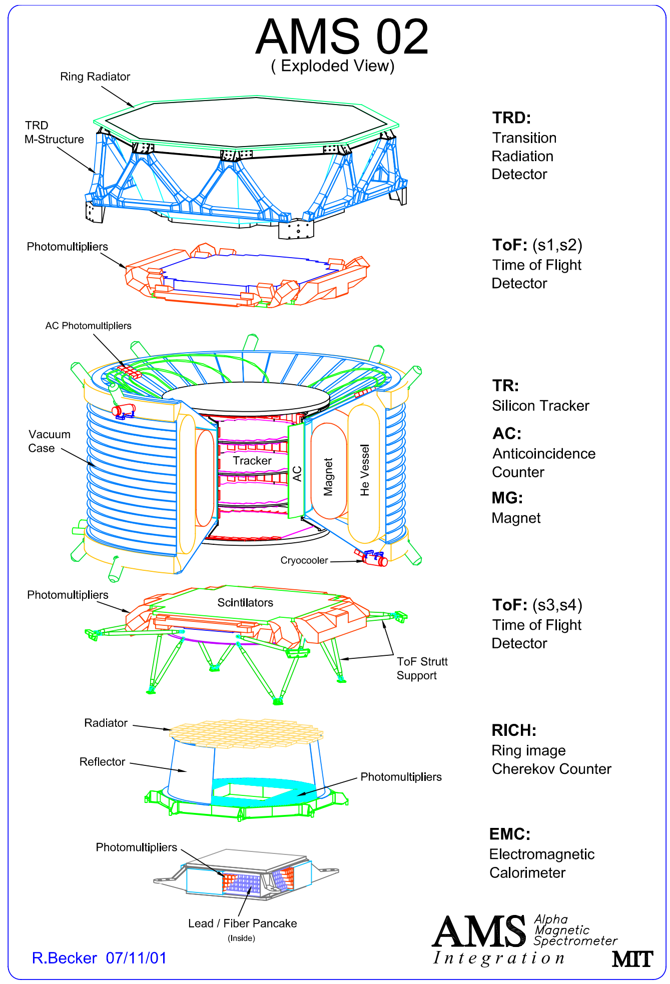

Fig. 1. Exploded view of the AMS-02 detector.

The long exposure time and large acceptance (0.5 m^{2}sr) of

AMS-02 will enable it to collect an unprecedented statistics of more than 10^{10} nuclei.

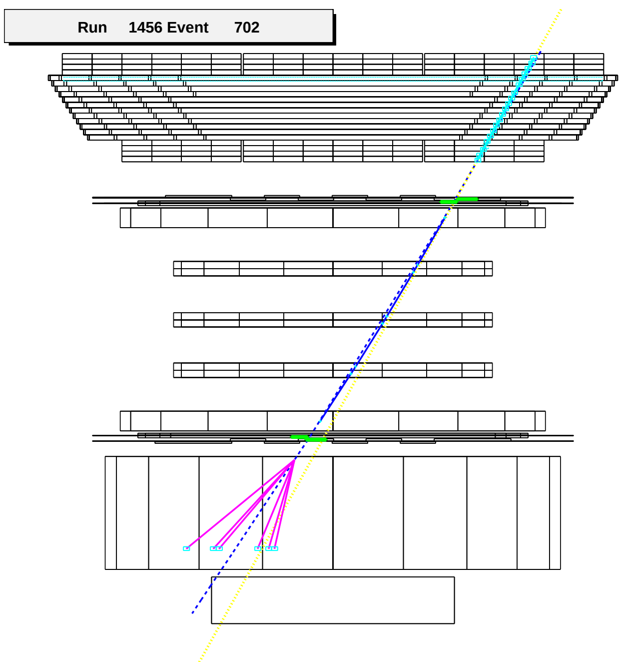

Fig. 2. A simulated proton event as seen in the AMS-02 display.

II. The AMS RICH Detector

One of the subdetectors in AMS-02 is a proximity focusing Ring Imaging Čerenkov (RICH) detector. It is composed of a dual radiator with silica aerogel ($n = 1.050$) and sodium fluoride ($n = 1.334$), a high reflectivity lateral conical mirror and a detection matrix with 680 photomultipliers coupled to light guides.

The RICH detector will provide a very accurate velocity measurement (in aerogel, = 10 ^{3} and 10 ^{4} for $Z = 1$ and $Z = 10$ 20, respectively) and charge identification of nuclei up to iron ($Z = 26$).

RICH data, combined with information on particle rigidity from the AMS Silicon Tracker, enable the reconstruction of particle mass. A typical RICH event is shown in Figs. 2 and 3, where the latter gives a detailed view of the readout matrix. The accuracy of the RICH velocity measurement is essential due to the growth of relative errors when $v \,!\, c$:

$$\frac{m}{m} = \frac{p}{p} \quad {}^{2} \_\_\_$$

The assembly of the AMS RICH detector is currently underway at CIEMAT in Madrid. The integration of the RICH and the other subdetectors of AMS-02 will take place at CERN in 2007.

The analysis of RICH data involves the identification of the Čerenkov ring in a hit pattern which usually includes several scattered noise hits and an eventual strong spot in the region where the charged particle crosses the detection plane. Two independent algorithms for velocity and charge reconstruction have been developed in the AMS collaboration for the analysis

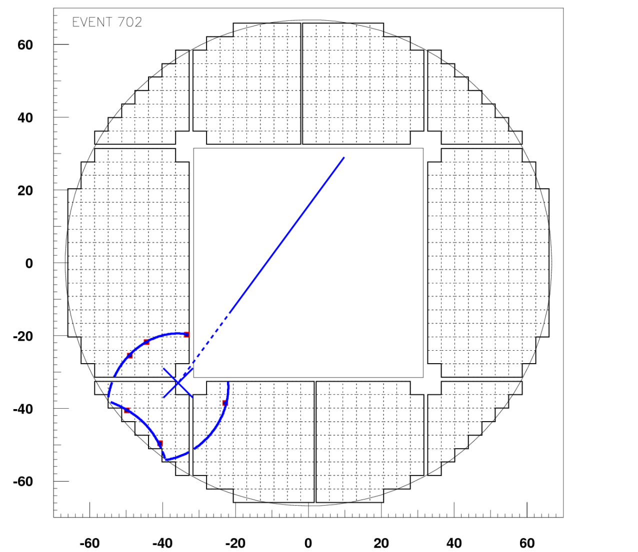

Fig. 3. The same event of Fig. 2 as seen in the RICH display developed at LIP.

of RICH events: a geometrical method based on a hit-by-hit reconstruction[2], and a method using all the hits with the maximization of a likelihood function[3]).

A prototype of the RICH detector, consisting of 96 photomultiplier units, was tested both with cosmic ray particles and with beam ions at the CERN SPS in 2002 and 2003. A piece of the conical reflector was included in the beam test setup[5]. The algorithms for velocity and charge reconstruction were successfully applied to data from these prototype tests[4].

III. Dark Matter and the Antideuteron Signal

Dark matter has been the subject of astrophysical research since the first half of the 20th century. Measurements of galactic rotation curves and of relative velocities of objects in galaxy clusters have shown that the total mass of galaxies and clusters is much higher than the mass of what is directly observed as luminous matter[6].

In recent years major progress has been made on this subject. The most recent cosmological data from WMAP[7] indicate that baryons account for only a small fraction of the total matter density of the Universe ($_{b}$ 0.04, $_{m}$ 0.24). The remaining mass should correspond to particles that have not been observed yet.

The neutralino ( ), a heavy, neutral, stable particle predicted by supersymmetric models, is a favourite dark matter candidate. If supersymmetry exists, the annihilation of neutralino pairs is expected to produce a significant effect on certain components of the cosmic ray spectrum (namely , e^{+}, p, D). In particular, the low energy antideuteron flux resulting from neutralino annihilation is expected to be orders of magnitude higher than the secondary flux due to other interactions[8], as shown in Figs. 4 and 5.

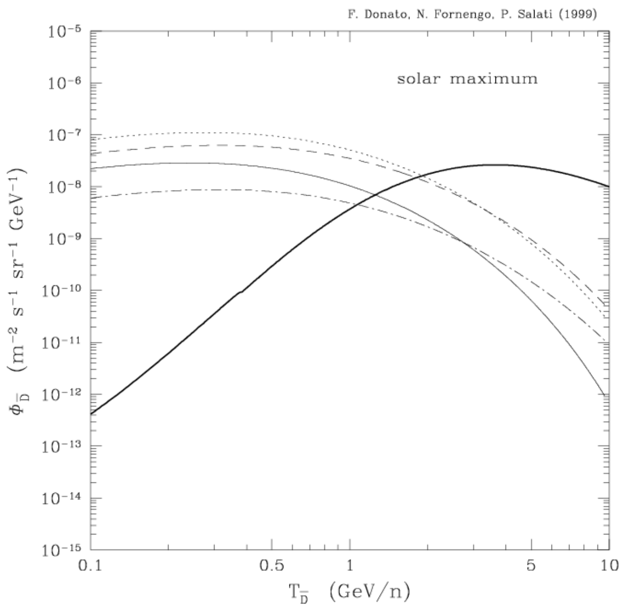

Fig. 4. Comparison of expected antideuteron fluxes from secondary processes and neutralino annihilation: solar maximum. The four cases shown for annihilation correspond to different sets of parameters in the context of the Minimal Supersymmetric extension of the Standard Model (MSSM) (from Ref. [8])

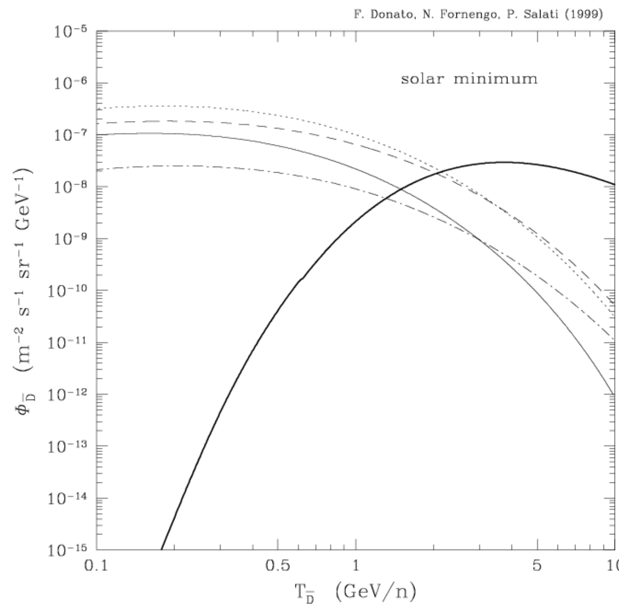

Fig. 5. Same as fig. 4, for solar minimum. (from Ref. [8])

IV. Particle identification: the deuteron case

To evaluate the capabilities of AMS-02 for mass separation of antideuterons from other particles with the same charge, studies have been performed using the similar case of deuteron vs. proton separation. In the past, studies on the separation of helium ($Z = 2$) and beryllium ($Z = 4$) isotopes have also been performed using a standalone simulation of the RICH detector[9]. In the present case the large difference between proton and deuteron abundances (D/p 1%) increases the importance of a very effective mass separation to isolate the deuteron signal from a large background of proton events.

In the study of D/p separation a full-scale simulation of the AMS detector was used. Particles were simulated as coming from the top plane of a cube, corresponding to an acceptance of 47.78 m^{2}sr. Three data samples were chosen. Table I shows the momentum ranges and number of events simulated in each sample.

TABLE I

Samples used in the D/p separation studies

Sample	Momentum range	No. events
p (low momentum)	0.5 10 GeV/c	3.1 10^8
p (high momentum)	10 200 GeV/c	1.3 10^8
D	0.5 20 GeV/c	5.6 10^7

For each sample, $\frac{dN}{d(\ln p)} =$ constant. Variable weights were assigned to events in order to compensate for the statistics in each sample and to reproduce a realistic spectrum (Fig. 6):

- The simulated proton spectrum followed $dN/dE \propto E^{-2.7}$;
- The simulated deuteron spectrum was calculated combining the proton spectrum above with D/p ratios taken from

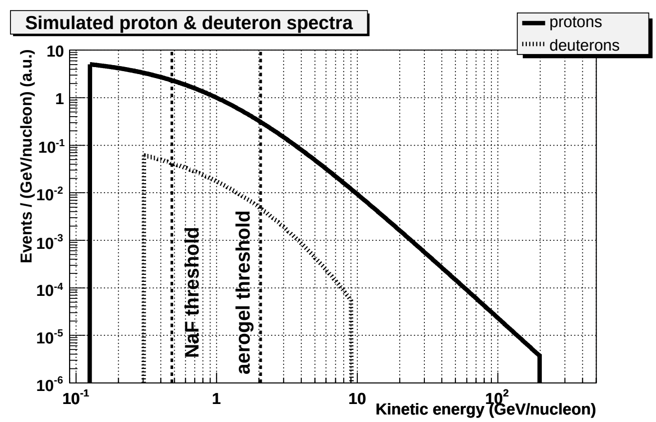

Fig. 6. Simulated proton and deuteron spectra used in this work.

Ref. [10].

In each event a set of preliminary data selection cuts using readings from different subdetectors of AMS-02 was applied to reduce the fraction of events with a bad reconstruction. Only downgoing events ($ > 0$) were accepted. In addition, events were accepted if the following conditions were satisfied:

- Only one particle was detected in the event;
- A particle track was reconstructed by the Silicon Tracker;
- No clusters were found in the Anti-Coincidence Counters;
- Clusters from at least 3 TOF planes (out of 4) were used for event reconstruction;
- At most one additional cluster was allowed in the TOF;
- At least 6 Tracker layers (out of 8) were used in the track reconstruction;
- Compatibility was required for the rigidity measurements obtained from two different algorithms, with $R/R < 3\%$;
- Compatibility was also required for the rigidity measure-

ments obtained from each half of the Tracker (upper and lower), with $R{=}R < 50\%$;

The particle's impact point on the RICH radiator was less than 58 cm from the centre (i. e. more than 2 cm from the mirror);

At most one track was present in the TRD;

The TOF and Tracker charge reconstructions were compatible.

Among the events that triggered the detector, a fraction corresponding to 15-20% of proton events and 10-15% of deuteron events in the relevant region of kinetic energy (few GeV/nucleon) passed this set of preliminary cuts, corresponding to an acceptance of 0.3 m^2sr for protons and 0.2 m^2sr for deuterons.

The reconstruction of particle masses was then performed for events having a signal in the RICH detector. The extremely accurate velocity measurement provided by the RICH (= 10^{3} in the case of protons and deuterons) is crucial to reduce the background level. A series of event selection cuts were introduced, based on data provided by the RICH and the results of the two reconstruction algorithms:

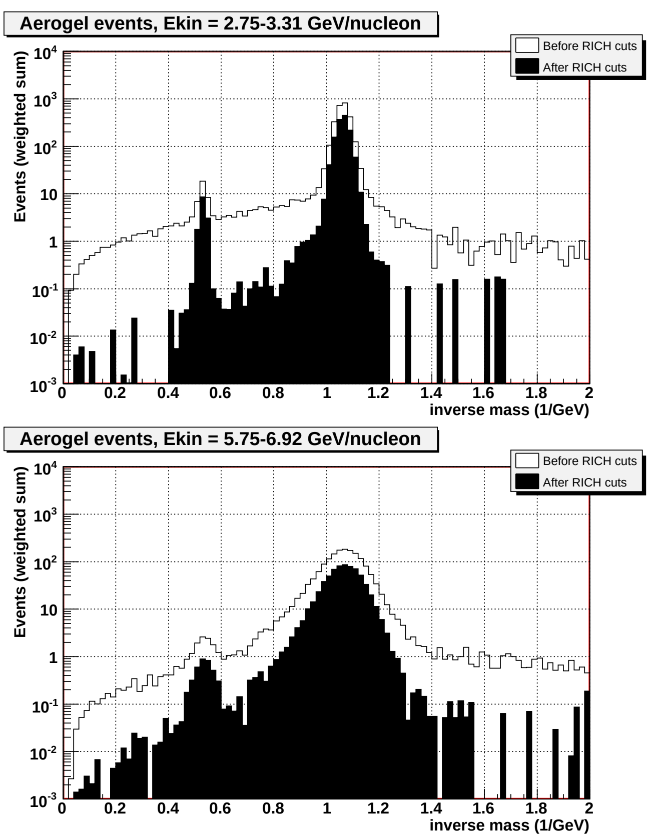

Fig. 7. Examples of inverse mass distribution in aerogel events for two energy regions.

A Čerenkov ring was reconstructed using each method, and at least 3 hits were used in both cases;

The number of ring hits was not higher than 10 in NaF events, and not higher than 15 in aerogel events;

A Kolmogorov test to the uniformity of the hits azimuthal distribution in the ring gave a result of at least 0.2 in the case of NaF events, and 0.03 in the case of aerogel events;

Compatibility was required for the velocity measurements from the TOF and RICH detectors, with $= < 10\%$;

Compatibility was also required for the velocity measurements obtained from the two RICH reconstruction methods, with $= < 0{:}3\%$ for NaF events, and $= < 0{:}07\%$ for aerogel events;

The reconstructed, rounded electric charge obtained from the geometrical method was 1 or 2;

The reconstructed, non-rounded electric charge obtained from the likelihood method was between 0.5 and 1.5 in NaF events, and between 0.6 and 1.4 in aerogel events;

The ring acceptance (visible fraction), as estimated by the likelihood method, was at least 20% in NaF events, and at least 40% in aerogel events;

The number of noisy hits not associated to the crossing of the charged particle (i. e., hits that were far from the reconstructed ring and far from the estimated crossing point of the charged particle in the detection matrix) was not higher than 2 in NaF events, and not higher than 4 in aerogel events.

V. Analysis results

Results show that mass separation of particles with $Z = 1$ is feasible even if one species is orders of magnitude more abundant than the other. D/p separation is possible up to E_{kin} 8 GeV/nucleon. Some examples of the mass distributions obtained are shown in Figs. 7 and 8. Solid lines show the mass distributions before the RICH cuts were taken into consideration.

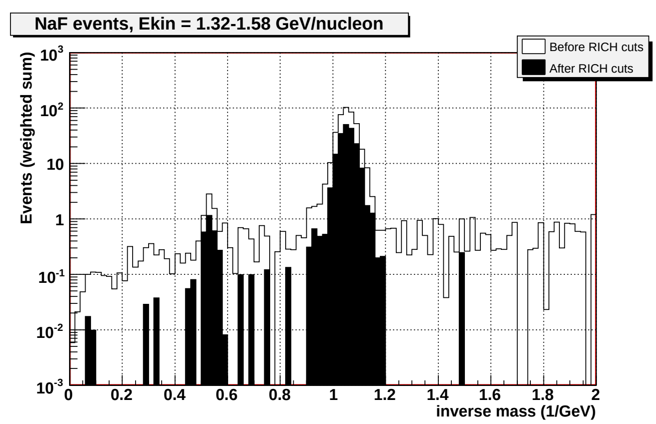

Fig. 8. Example of inverse mass distribution in NaF events.

In the optimal region immediately above the aerogel radiation threshold ($E_{kin} = 2.1$ 4 GeV/nucleon) rejection factors in the 10^3 10^4 region were attained (Fig. 9). The best relative mass resolutions for protons (Fig. 10) and deuterons are 2% for both radiators in the regions above their respective thresholds.

After all cuts, an acceptance of 0.06 m^2sr was obtained for protons, and 0.04 m^2sr for deuterons at

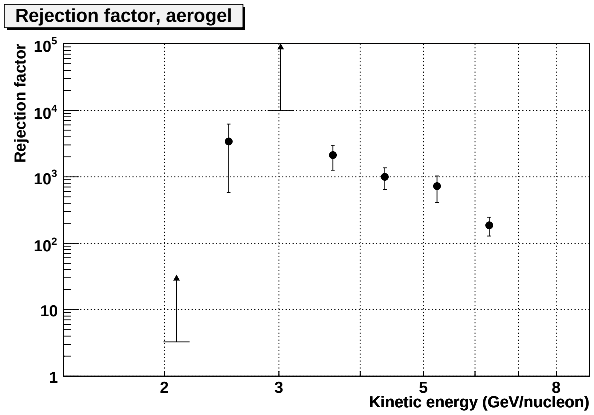

Fig. 9. Rejection factor for D/p separation in aerogel events.

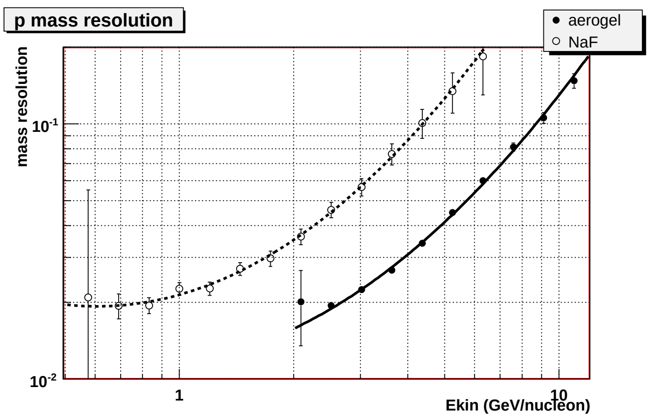

Fig. 10. Relative mass resolution for protons: NaF events (open dots) and aerogel events (filled dots).

$E_{kin} > 3$ GeV/nucleon (Fig. 11). The increase by a factor 10 in the acceptance above the aerogel threshold reflects the relative dimensions of the two radiators in the RICH detector.

The main background in the deuteron case comes from non-gaussian tails of proton events with a bad velocity reconstruction. Errors in rigidity reconstruction ($\Delta R/R \sim 2\%$ in the GeV region) are not critical for this case.

The specific set of cuts shown here corresponds to an example of a selection procedure. Other variations are possible. In particular, rejection factors may be improved by applying stricter cuts, at the expense of a further acceptance reduction.

VI. Conclusions

AMS-02 will provide a major improvement on the current knowledge of cosmic rays. A total statistics of more than 10^{10} events will be collected during its operation. Detailed simulations have been performed to evaluate the detector's particle identification capabilities, in particular those of the RICH, which might be crucial for the identification of an antideuteron flux resulting from neutralino annihilation. Simulation results show that the separation of light isotopes is feasible. Using a set of simple cuts based on event data, relative mass resolutions of ~ 2 % and rejection factors up to 10^4 have been attained in D/p separation at energies of a few GeV/nucleon.

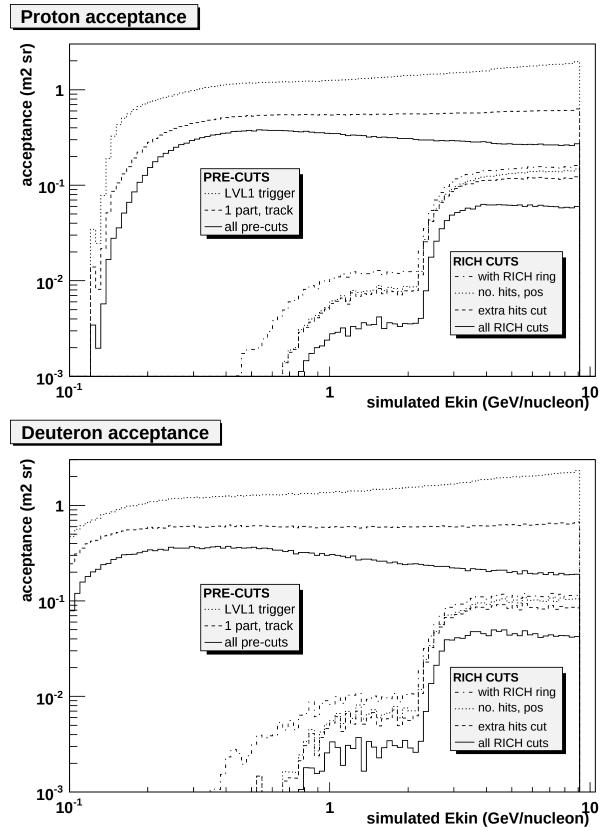

Fig. 11. Acceptance for protons (top) and deuterons (bottom) at different stages of event analysis. Solid lines correspond to acceptances after the preliminary cuts (third line from top) and after all cuts (lower line).

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