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Experimental method to measure the positron fraction in AMS-02

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The Alpha Magnetic Spectrometer AMS-02 is a high energy particle physics detector, operational on the International Space Station since May 2011. The AMS-02 goal is the fundamental physics research in space with high energy cosmic rays, during its 20 year duration mission. The latest published results, with 30 months of data, show an excess of high energy positrons whose origin is still highly uncertain. These positrons, in addition to being produced by spallation of cosmic rays on interstellar medium, may be produced in nearby pulsars, annihilation of dark matter particles, or still unknow processes. In this proceeding, the analysis technique used for measuring positron fraction is presented. This analysis is based on three subdetectors: the Transition Radiation Detector (TRD), the silicium tracker, and the Electromagnetic CALorimeter (ECAL). we discuss a method which allows the combination of estimators constructed from these three subdetectors, in order to separate first leptons and protons, and secondly positrons and electrons. We also detail the influence and the determination of the charge confusion between the positrons and electrons at high energy.

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1. Introduction

The first measurement by PAMELA [1] of an increase on the positron fraction below 10 GeV has created a strong interest. The positron fraction is defined as the ratio of the positron flux to the combined flux of positrons and electrons $\frac{\phi_{e^+}}{\phi_{e^+ + e^-}}$. The new result of the AMS-02 experiment has recently confirmed [2], with an unprecedently accuracy, this behavior of the positron fraction. This result confirmed an excess of positrons with respect to the astrophysical background produced by interactions of high-energy protons and helium nuclei with the interstellar medium.

The AMS-02 detector (Fig 1) is composed of five sub-detectors which performed redundant measurements of the particle characteristic. The silicon tracker of nine planes combined with a permanent magnet measures charge, sign of the charge, and momentum. The Transition Radiation Detector (TRD) identifies the particle as leptons or protons related to their Lorentz factor. The four planes of the Time Of Flight (TOF) counters measure the absolute charge and the direction of the particle. The Ring Imaging CHerenkov detector (RICH) measures the charge and the velocity of the particle. The Electromagnetic CALorimeter (ECAL) is composed of nine superlayers along the z-axis of AMS-02, with fibers in alternating directions in order to reconstruct x and y position of the energy deposition.

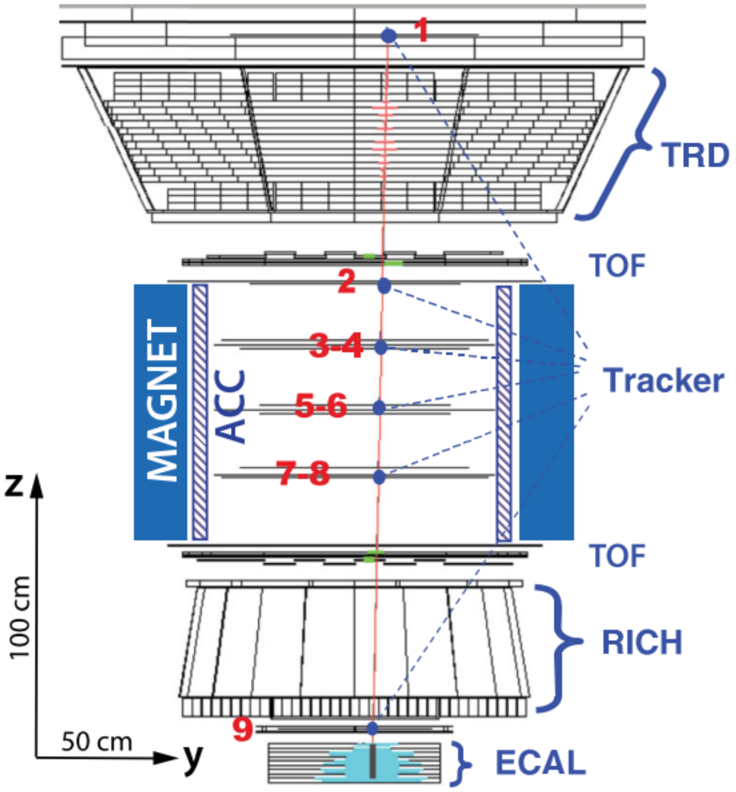


Figure 1: A 369 GeV positron event as measured by the AMS detector on the ISS.

In this proceeding, an analysis method to measure the positron fraction with data collected during 30 months of AMS operations is described. This method is an alternative approach used as a crosscheck of the AMS-02 positron fraction official analysis. This method combines the TRD, the ECAL, and the tracker in order to count electrons and positrons, and to evaluate charge confusion.

2. Analysis method

2.1 General overview

The main challenge of the analysis of the positron fraction is the separation between nucleus background (mainly protons) and leptons. The three main AMS sub-detectors used in this analysis are the TRD, the tracker, and the calorimeter. The deposited energy trough the TRD, the shower shape in the calorimeter, and the ratio $\frac{E}{p}$ between the momentum p measured by the tracker and the deposited energy E in the calorimeter permits to distinguish background and leptons. The second main challenge is the measurement of the charge sign of the leptons in order to separate electrons and positrons. The permanent magnet curves the trajectory of the particles because of the Lorentz force, and allows to determine the sign of the charge. However, at high energy, due to the small curvature of the trajectory and to the secondary particles produced trough the tracker, distinction of electrons and positrons becomes challenging. This effect, called charge confusion, has to be estimated and corrected.

2.2 Data sample

The analysis presented in this proceeding is using data collected during 30 months of AMS operations on the International Space Station, from 19 May 2011 to 26 November 2013. A preselection is performed in order to isolate lepton-like events from background-like events and to ensure a selection of well-reconstructed events. We require a track in the TRD and in the tracker, and an energy deposition in the ECAL. The β measured by the TOF is required to be $\simeq 1$. A good track reconstruction in the tracker is required with a selection on the χ^2 of the fitted track. In order to maximise the lever arm of the tracker, the event is required to deposit a hit on the layer 1, 2, or 9. A good matching between the track in the tracker and the axis of the electromagnetic shower is required. In order to reject positrons and electrons produced by the interaction of primary cosmic rays with the atmosphere, the energy measured with the ECAL is required to exceed the maximal Stoermer cutoff, multiplicated by a safety factor of 1.25, for either a positive or a negative particle at the geomagnetic location where the particle is detected and at any angle within the AMS acceptance. In order to suppress the helium background and to reduce the proton background, a selection on deposited energy divided by rigidity and apex position of the electromagnetic shower is performed.

2.3 3D template fit method

In order to determine, for each ECAL energy bin, the value of the positron fraction, template fit method is used on a three dimensional space (TRD estimator, ECAL estimator, charge sign estimator) simultaneously on negative and positive rigidity samples. The TRD estimator uses energy deposition trough the tubes of the TRD to discriminate protons from leptons. The ECAL estimator uses the shape of the shower on the ECAL to discriminate proton from leptons. The charge estimator uses the χ^2 of the track, the charges of the upper and lower TOF, and the charge of the tracker to discriminate charge-confused from good-sign events. For either the positive and negative rigidity samples, the positrons, electrons, and protons are populating different regions and are following different probability density functions (PDF). The knowledge of this three dimensional (3D) PDF allows us to fit the normalisation of this PDFs on this 3D space which permits the evaluation of the number of positrons and electrons, taking into account the migration between positive and negative rigidity space due to charge confusion.

2.3.1 PDF estimation method

The PDF of every species (positrons, electrons, and protons) is estimated on ISS data for the TRD estimator and the ECAL estimator. Pure electron and proton samples are produced on data with a tight selection on the TRD estimator or ECAL estimator. Electrons and positrons are following the same PDF on each estimator space, which permits to evaluate the positron PDF on the electron sample to reduce the proton pollution. A Novosibirsk function is used to modelise the spectrum of the event on the TRD estimator and ECAL estimator space:

$$\mathscr{P}_{\text{Novo}} = A\exp\left[\frac{-\ln^2\left(1+t\Lambda\dfrac{x-\mu}{\sigma}\right)}{2t^2}-\frac{t^2}{2}\right], \tag{2.1}$$

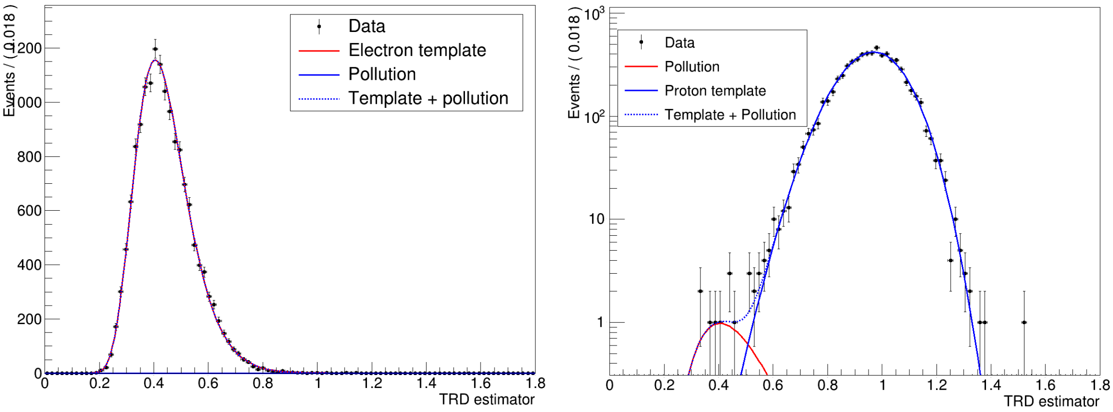
where A is the normalisation, $\Lambda = \sinh(t\sqrt{\ln 4})/(t\sqrt{\ln 4})$, and with x the variable, μ its distribution mean, σ its width, and t a parameter governing the tail behavior. This function approaches a Gaussian function when the parameter $t \to 0$. The three parameters of the function are computed with a fit on the pure proton and electron samples. The fit is performed simultaneously on proton and electron templates, in order to evaluate and correct the pollution of the template. At high energy, the proton template shows differences between good reconstructed rigidity and bad reconstructed rigidity events, this effect is taken into account and corrected. Figure 2 shows example of this template fit.

The PDFs of wrong-sign and good-sign electrons, in the charge sign estimator space, are obtained on Monte Carlo for electrons and on the data for the protons. Pure proton sample on data is selected with a tight selection on ECAL estimator and TRD estimator. The PDF is estimated as the histogram of the number of event divided by the normalisation. Figure 3 shows pure samples and associated PDF for protons, wrong-sign and good-sign templates.

Because estimators are uncorrelated, the 3D PDF for each species is the multiplication of the one dimensional (1D) PDF. With the multiplication of the 1D PDFs obtained above, the 3D PDFs are evaluated for every species present on the positive and negative datasets: wrong-sign positrons ($\mathscr{P}_{WS,e^{+/-}}$), good-sign positrons ($\mathscr{P}_{GS,e^{+/-}}$), wrong-sign electrons ($\mathscr{P}_{WS,e^{+/-}}$), good-sign electrons ($\mathscr{P}_{GS,e^{+/-}}$), and protons ($\mathscr{P}_p$).

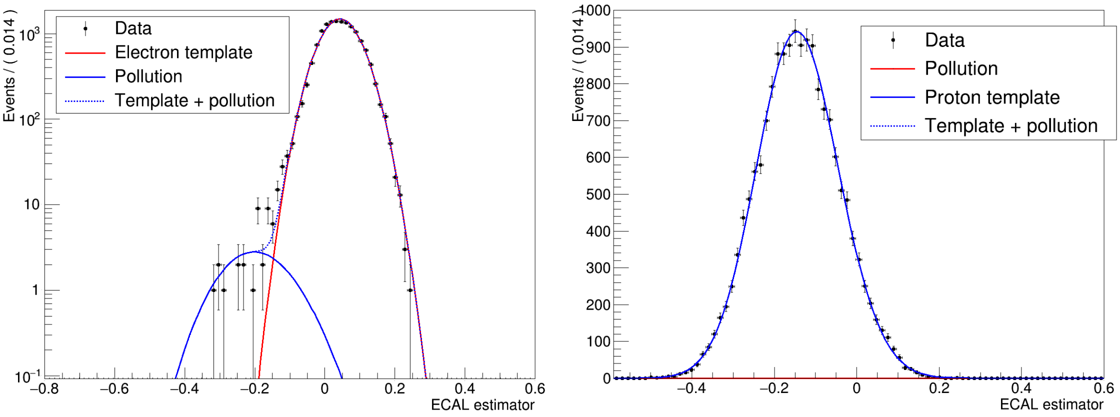
2.3.2 Lepton and positron count and charge confusion measurement

The counting is performed simultaneously on negative rigidity and positive rigidity datasets. The positive rigidity sample contains positrons with a good sign, electrons with a wrong sign, and protons. The negative rigidity sample contains electrons with a good sign, protons, and a negligible number of positrons with a wrong sign. In the following, the charge confusion factor (C_f) is defined



(a) Electron sample with the fitted PDF for the TRD estimator in the energy bin $27.34-28.87$ GeV.

(b) Proton sample with the fitted PDF for the TRD estimator in the energy bin $27.34-28.87$ GeV.



(c) Electron sample with the fitted PDF for the ECAL estimator in the energy bin $27.34-28.87$ GeV.

(d) Proton sample with the fitted PDF for the ECAL estimator in the energy bin $27.34-28.87$ GeV.

Figure 2: Example of templates used for the analysis. The dots are the ISS data whereas the line represents the PDF.

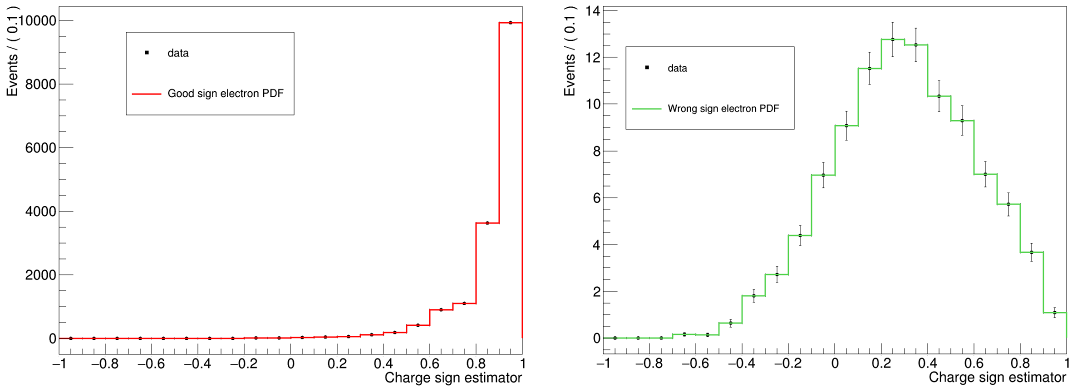
as $C_f = \frac{N_{WS}}{N_{GS}+N_{WS}}$, and is the probability for an event to be reconstructed with a wrong sign. On the positive sample, the distribution of the event are following this formula:

$$C_f N_{e^-} \mathscr{P}_{WS,e^{+/-}} + (1-C_f) N_{e^+} \mathscr{P}_{GS,e^{+/-}} + N_{p^+} \mathscr{P}_p,$$

and for the negative sample:

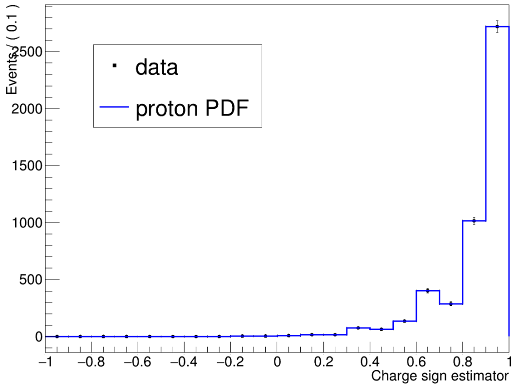
$$C_f N_{e^+} \mathscr{P}_{WS,e^{+/-}} + (1-C_f) N_{e^-} \mathscr{P}_{GS,e^{+/-}} + N_{p^-} \mathscr{P}_p,$$

where N_{e^-} is the electron number, N_{e^+} the positron number, C_f the charge confusion factor, N_{p^+} the proton number with a positive rigidity, N_{p^-} the negative rigidity proton-like number (mainly charge confused protons). These parameters are fitted on the datasets with a maximum likelihood method by `MINUIT` and the uncertainty of the parameters are computed by `MIGRAD`. The influence of the uncertainty in C_f and N_p and correlations between free parameters are taken into account in the final uncertainty of N_{e^-} and N_{e^+}. A fit example is presented on Figs. 4 and 5.



(a) Electron good-sign template.

(b) Electron wrong-sign template.



(c) Proton template.

Figure 3: Charge sign estimator templates for the energy bin of 27.34 – 28.87 GeV.

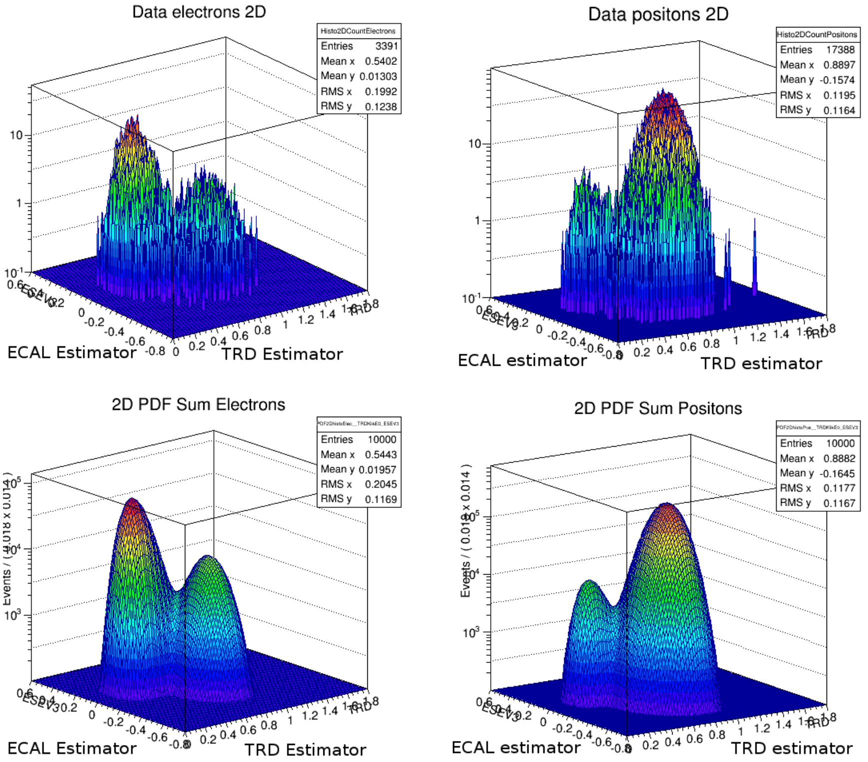
2.4 Result and conclusions

For each energy bin, 3D fits of the normalisation of the 3D PDFs detailed in the previous section are performed in order to count the number of positrons and electrons, and the positron fraction is computed. The results of this analysis, presented as an alternative approach used as a crosscheck, are compatible with the official analysis [2] (Fig. 6).

This result of AMS-02 confirms, with an unprecedented precision and at higher energy, a rise in the positron fraction beyond 8 GeV and a tendency to decrease beyond 350 GeV. This increase confirms the presence of a primary source of positrons. Pulsars and annihilating WIMPs are frequently quoted as possible sources of this positron excess [3]. A precise knowledge of the shape of the positron fraction, particularly at high energy, will help in the future to identify this primary source of positrons.

References

[1] Adriani, O. *et al.*, *An anomalous positron abundance in cosmic rays with energies* 1.5 – 100 *GeV*, *Nature* **458** (7238).



(a) Top: negative sample data. Bottom: negative sample 2D fit; left peak is electrons and right peak is negative rigidity protons.

(b) Top: positive sample data. Bottom: positive sample 3D fit projection on TRD estimator and ECAL estimator axis; left peak is positrons and right peak is protons.

Figure 4: Fit example for the 92.5 – 100 GeV energy bin.

[2] Accardo, L. *et al.*, *High Statistics Measurement of the Positron Fraction in Primary Cosmic Rays of* 0.5 – 500 *GeV with the Alpha Magnetic Spectrometer on the International Space Station*, *Physical Review Letters* **113** (121101).

[3] Boudaud, M. *et al.*, *A new look at the cosmic ray positron fraction*, *Astronomy & Astrophysics* **575** (A67).

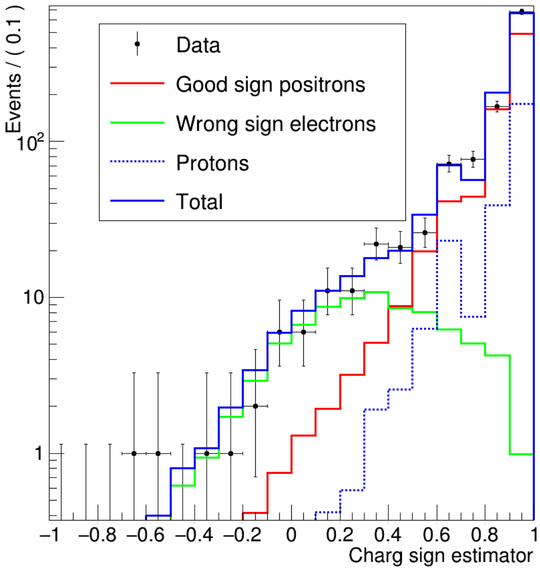


Figure 5: Fit example for the 50.87 – 54.98 GeV energy bin. Positive sample 3D fit projection on charge sign estimator with a selection on ESE and TRD. The green histogram represents the charge confused electrons, the blue dashed blue histogram the protons, and the red histogram the positons.

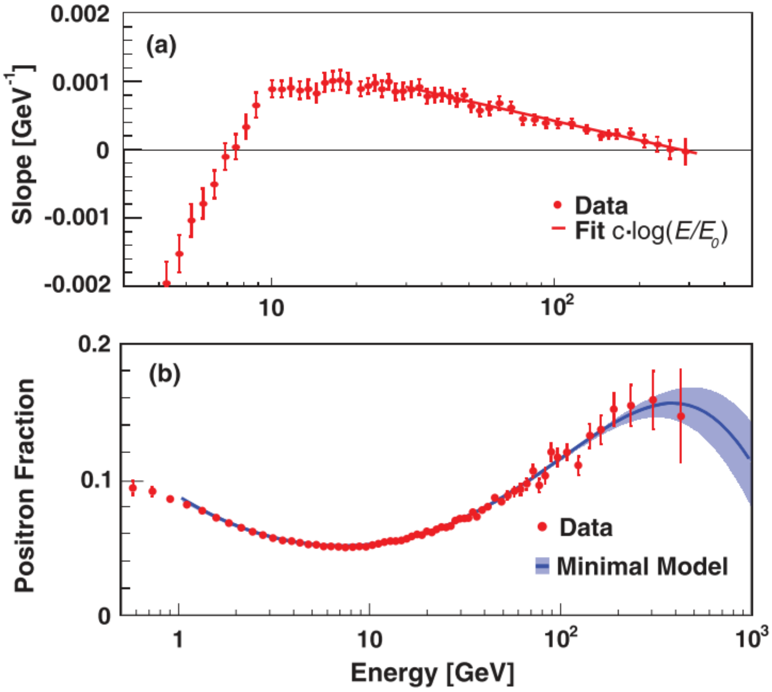


Figure 6: (a) The slope of the positron fraction vs energy over the entire energy range (the values of the slope below 4 GeV are off scale). The line is a logarithmic fit to the data above 30 GeV. (b) The positron fraction measured byAMS and the fit of a minimal model (solid curve, see [2]) and the 68% C.L. range of the fit parameters (shaded). For this fit, both the data and the model are integrated over the bin width. The error bars are the quadratic sum of the statistical and systematic uncertainties. Horizontally, the points are placed at the center of each bin.