Isotopes identification in AMS

Application of a data-driven method

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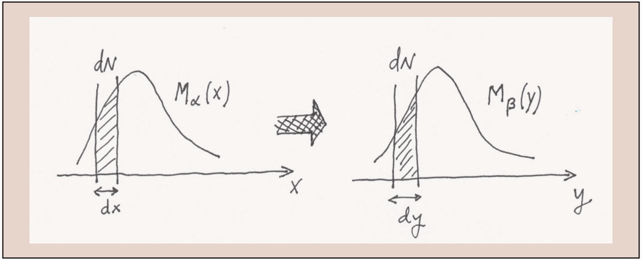
LIP/IST



Talk Overview

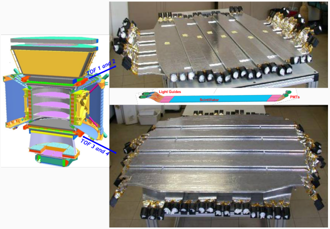
- ✔ **AMS detector**
  - ✔ isotopic identification
  - ✔ important sub-detectors to isotope identification
  - ✔ important physical observables
- ✔ **Isotopes Simulation**
  - ✔ isotopes simulation: toy model
  - ✔ mass templates
- ✔ **Data Driven Method**
  - ✔ problem statement
  - ✔ iterative process
  - ✔ model evaluation - χ^2
  - ✔ implementation
- ✔ **Final remarks**

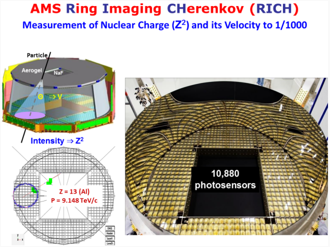
AMS detector

- ✔ It is a module which has several particle detectors that is mounted on the ISS
- ✔ Main objectives:
  - ➔ Search for antimatter
  - ➔ Origin of dark matter
  - ➔ Precision study of CR

Isotopic Identification

- ✔ **Why?**
  - ➔ CR propagation processes
  - ➔ Structure of the magnetic fields in the galactic halo
- ✔ **How?**
  - ➔ Silicon Tracker
  - ➔ Time of Flight (ToF)
  - ➔ Ring Imaging Cherenkov Detector (RICH)
    - ➔ NaF - (sodium fluoride)
    - ➔ AGL - (aerogel)





Physical Observables

The physical observables that we measure with the detectors are:

- ✔ Charge, Z
- ✔ Velocity, β
- ✔ Rigidity, $R = \frac{p}{Z}$

With these quantities we are able to calculate the particles mass

- ✔ Mass, $m = \frac{RZ}{\gamma\beta}$

Isotopes Simulation

Cosmic Ray Flux - Particle Generation

To simulate a particle with a given (Z, A):

- ➔ Generate a random T_n from the function of the cosmic ray flux, $J(T_n)$
- ➔ Calculate the true velocity of this particle, β
  $\beta(Tn) = \frac{\sqrt{T_n(T_n+2mc^2)}}{T_n+mc^2}$
- ➔ Calculate true rigidity, R
  $R(\beta, T_n) = \frac{A}{Z}\beta\left(T_n + mc^2\right)$

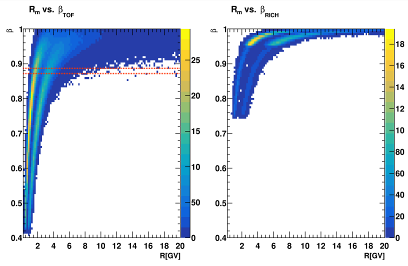
Simulating Measurement

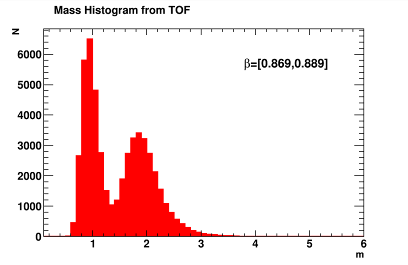
Now we need to simulate the detection of our particles in the detectors and the measurement of their properties (rigidity and velocity)

- ✔ Rigidity - measured by the Tracker
- ✔ Velocity - measured by
  - ➔ TOF
  - ➔ RICH NAF
  - ➔ RICH aerogel

Isotopes Simulation - Mass Distributions

The following histograms correspond to data of a simulated detection of two isotopes with $A = \{1, 2\}$ with relative fractions 0,5.



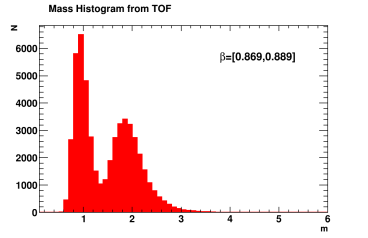


Data Driven Method

Problem Statement

The problem is the following:

- ✔ A mass histogram is provided (simulated or experimental)
- ✔ A set of isotopes is present
- ✔ **Questions**
  - ➔ What are the fractions of each isotope?
  - ➔ What are the isotope mass templates?



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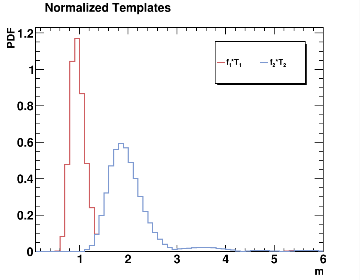

Solutions to the problem

This problem can be solved with different approaches

- → Analytical approach
- → Parametric approach
- → **Data Driven Method**

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A parametric approach for the identification of single-charged isotopes with AMS-02

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ABSTRACT

Measurements of the isotopic composition of single-charged cosmic rays provide important insights in the propagation processes. However, the isotopic identification is challenging due to the one hundred times greater abundance of protons when compared to deuterons, the only stable isotope of hydrogen. Taking advantage of the precise measurements of the velocity and momentum in the Alpha Magnetic Spectrometer (AMS-02), a particle physics detector operating aboard the International Space Station since May 2011, we describe a parametric template fit method, which takes into account systematic uncertainties such as the fragmentation of particles inside AMS-02 and eventual differences between data and simulation through the use of nuisance parameters. With this method we are also able to assess the AMS-02 performance in terms of mass resolution, showing that it is able to separate the isotopes of hydrogen up to 10 GeV/n.

proceedings

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Article

A Data Driven approach for the measurement of $^{10}Be/^{9}Be$ in Cosmic Rays with magnetic spectrometers.

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Abstract: Cosmic Rays (CR) are a powerful tool for the investigation of the structure of the magnetic fields in the galactic halo and the properties of the Inter-Stellar Medium. Two parameters of the CR propagation models: the galactic halo (half-) thickness, H, and the diffusion coefficient, D, are loosely constrained by current CR flux measurements, in particular a large degeneracy exist being only H/D well measured. The $^{10}Be/^{9}Be$ isotopic flux ratio (thanks to the 2 My lifetime of ^{10}Be) can be used as a radioactive clock providing the measurement of CR residence time in the galaxy. This is an important tool to solve the H/D degeneracy. Past measurements of $^{10}Be/^{9}Be$ isotopic flux ratio in CR are scarce, limited to low energy and affected by large uncertainties. Here a new technique to measure $^{10}Be/^{9}Be$ isotopic flux ratio, with a *Data-Driven* approach, in magnetic spectrometers is presented. As an example by applying the method to Beryllium events published by PAMELA experiment it is now possible to determine the important $^{10}Be/^{9}Be$ measurement avoiding the prohibitive uncertainties coming from the Monte Carlo simulation. It is shown how the accuracy of PAMELA data permits to infer a value of the halo thickness within 25% precision.

Keywords: astroparticle physics; cosmic rays; galactic halo

DDM Assumptions

The data driven method that will be presented next is built on top of 2 assumptions

- ➔ The mass resolution is equal for all the isotopes
- ➔ It is possible to transform one mass template into another with a linear tranformation

Assumptions - Equal mass resolution

$$\frac{\delta M}{M} = \sqrt{\left(\frac{\delta R}{R}\right)^2 + \gamma^4 \left(\frac{\delta \beta}{\beta}\right)^2}$$

- Mass distributions are made in small β bins so the velocity resolution is nearly constant

- The rigidity resolution is approximately constant in the low kinetic energy range

- If both β and R resolutions are constant so is the mass resolution

- If the isotopes have similar masses we can assume equal mass resolutions for them

$$\left(\frac{\delta M}{M}\right)_\alpha = \left(\frac{\delta M}{M}\right)_\lambda = \left(\frac{\delta M}{M}\right)_\theta$$

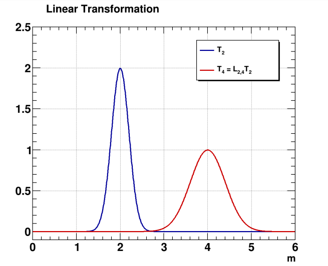
Linear Transformation

To transform from one template into another we apply the linear transformation:

$$T_\lambda(x) = aT_\alpha(ax) = \frac{\mu_\alpha}{\mu_\lambda} T_\alpha(\frac{\mu_\alpha}{\mu_\lambda} x)$$

We also introduce a notation to represent this linear transformation

$$T_\lambda(x) = \mathcal{L}_{\alpha,\lambda} T_\alpha \equiv \frac{\mu_\alpha}{\mu_\lambda} T_\alpha(\frac{\mu_\alpha}{\mu_\lambda} x)$$



Iterative Process: 2 Isotopes First Template

We can establish an iterative process to get one of the templates (root template), after defining a pair of guess fractions $\{f_\alpha, f_\lambda\}$

➔ $T_\alpha = \frac{1}{f_\alpha}\left(D - \frac{f_\lambda}{f_\alpha}\mathcal{L}_{\alpha,\lambda} D\right) + \left(\frac{f_\lambda}{f_\alpha}\right)^2 \mathcal{L}_{\alpha,f}\, T_\alpha$

➔ $T_\alpha^{(0)} = \frac{1}{f_\alpha}\left(D - \frac{f_\lambda}{f_\alpha}\mathcal{L}_{\alpha,\lambda} D\right)$

➔ $T_\alpha^{(1)} = T_\alpha^{(0)} + \left(\frac{f_\lambda}{f_\alpha}\right)^2 \mathcal{L}_{\alpha,f}\, T_\alpha^{(0)}$

➔ ...

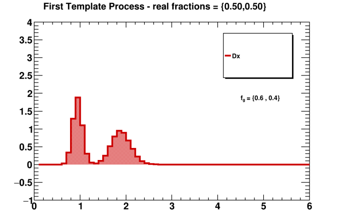
➔ $T_\alpha^{(k+1)} = T_\alpha^{(0)} + \left(\frac{f_\lambda}{f_\alpha}\right)^2 \mathcal{L}_{\alpha,f}\, T_\alpha^{(k)}$

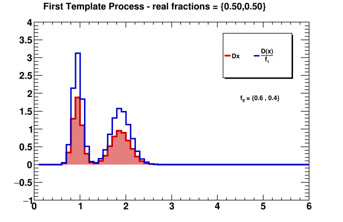
Construction of the 1st Template

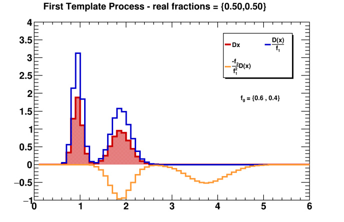
Example: construction of the 1st template for two isotopes from simulated data distribution (real fractions 0.5-0.5)

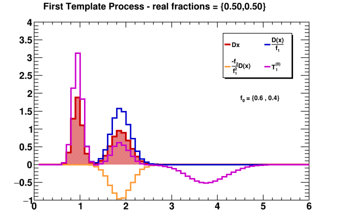
$$T_\alpha = \frac{1}{f_\alpha} D - \frac{f_\lambda}{f_\alpha^2} \mathcal{L}_{\alpha,\lambda} D$$

➔ Iteration 0





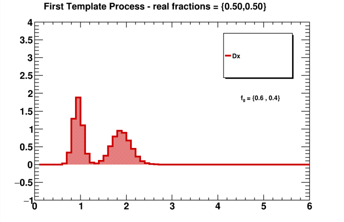


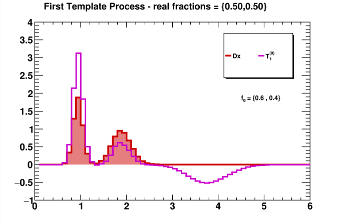


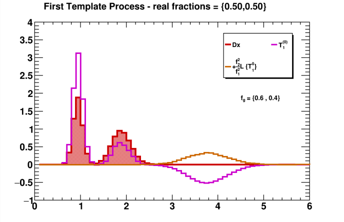
Construction of the 1st Template

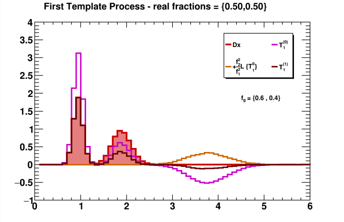
Example: construction of the 1st template for two isotopes from simulated data distribution (real fractions 0.5-0.5)

➔ Iteration 1









Iterative Process: 2 Isotopes Second Template and Model

Once we have determined the first template, we apply the linear transformation to get the second

- ➔ $T_\beta = \mathcal{L}_{\alpha,\beta} T_\alpha$

The model, M, is constructed from the two templates

- ➔ $M = f_\alpha T_\alpha + f_\beta T_\beta$

Model Evaluation

To assess whether the model corresponds to the experimental data we define an estimator χ^2

- ➔ At each bin we calculate a quantity one of two ways, where $N \equiv$ bin content
  - ➔ if the data bin content is 0, $\frac{(N_{data} - N_{model})^2}{|N_{model}|}$
  - ➔ if the data bin content is not 0 , $\frac{(N_{data} - N_{model})^2}{N_{data}}$
- ➔ With the estimator defined we can compare the models generated for various guess fractions. The guess fraction to which the smallest χ^2 corresponds should be the real fraction of the isotopes.

Implementation

To implement this method two main classes were developed:

- **uTransform** - has methods to perform a linear transformation on ROOT objects TF1 and TH1D (functions and histograms)
- **uIsotopesDDM** - receives an experimental/simulated mass distribution, has methods to perform each iterations of DDM and stores the mass templates and models in a map

Features of DDM

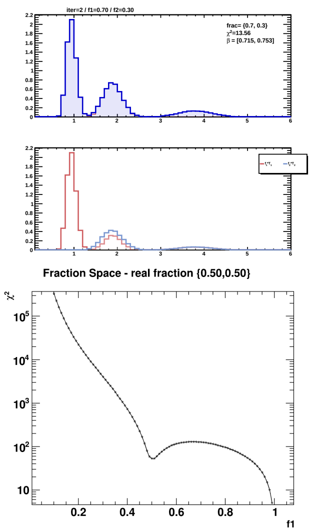
The data driven method has some problems/features we need to account for:

- ✔ The template *bins* acquire negative values (no physical meaning)
- ✔ We cannot identify a minimum of our estimator-χ^2 in the fraction parameter space
- ✔ The models obtained have "tails" whose mass values increase (exponencially) with the iteration. The problem of sectioning the histogram arises. To what extent does it make sense that our model exist?

Absolutify

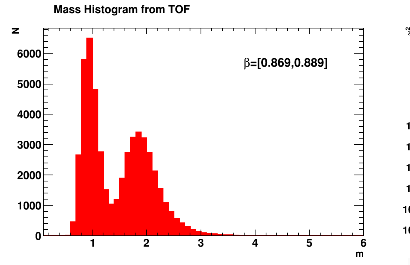
In order to solve the first and the second problem we *absolutify* our templates:

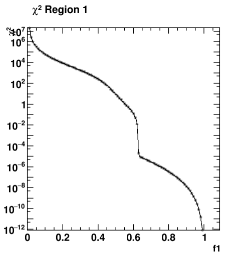
- ✔ Loop through all bins
- ✔ If the bin has negative content, set it to the absolute value of that number
- ✔ The tails are enhanced and allow to identify the minimum exist

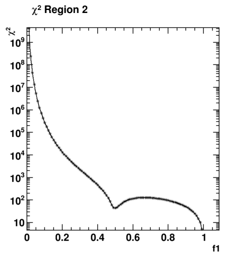


Final Procedure

- ✔ 1. Receive a total mass distribution
- ✔ 2. Find out which is the fraction by analysing the tails of the ABS "option" Model (minimum in χ^2 graph) with few iterations

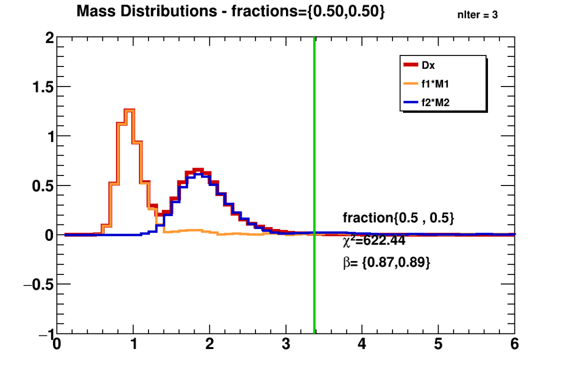






Final Procedure

- ✔ 3. Reset range of the templates to the region of interest (region where experimental distribution has positive values)
- ✔ 4. Normalize them in that region

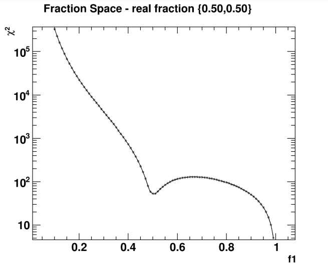


Conclusion

- ➔ We were able to implement the DDM purposed by [1]
- ➔ We could extract the correct fractions of the isotopes for the simulated mass distributions
- ➔ We could derive the mass templates having a reliable model in the end

Next Steps

- ➔ χ^2 minimization (travelling the parameter space)
- ➔ More realistic mass distributions (experimental data or more accurate simulations)



Thank you for your time!

Questions?

Contact me:

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References

1 Cernetti, C.; Nozzoli, F.; "A Data Driven Approach to the Measurement of 10Be/9Be in Cosmic Rays with Magnetic Spectrometers", *Phys. Sci. Forum* 2021, 2, 13.

2 Images on slides 3-4 are from `https://ams02.space/` (AMS-02 website)