Methods for cosmic-ray antideuteron identification with the AMS-02 experiment

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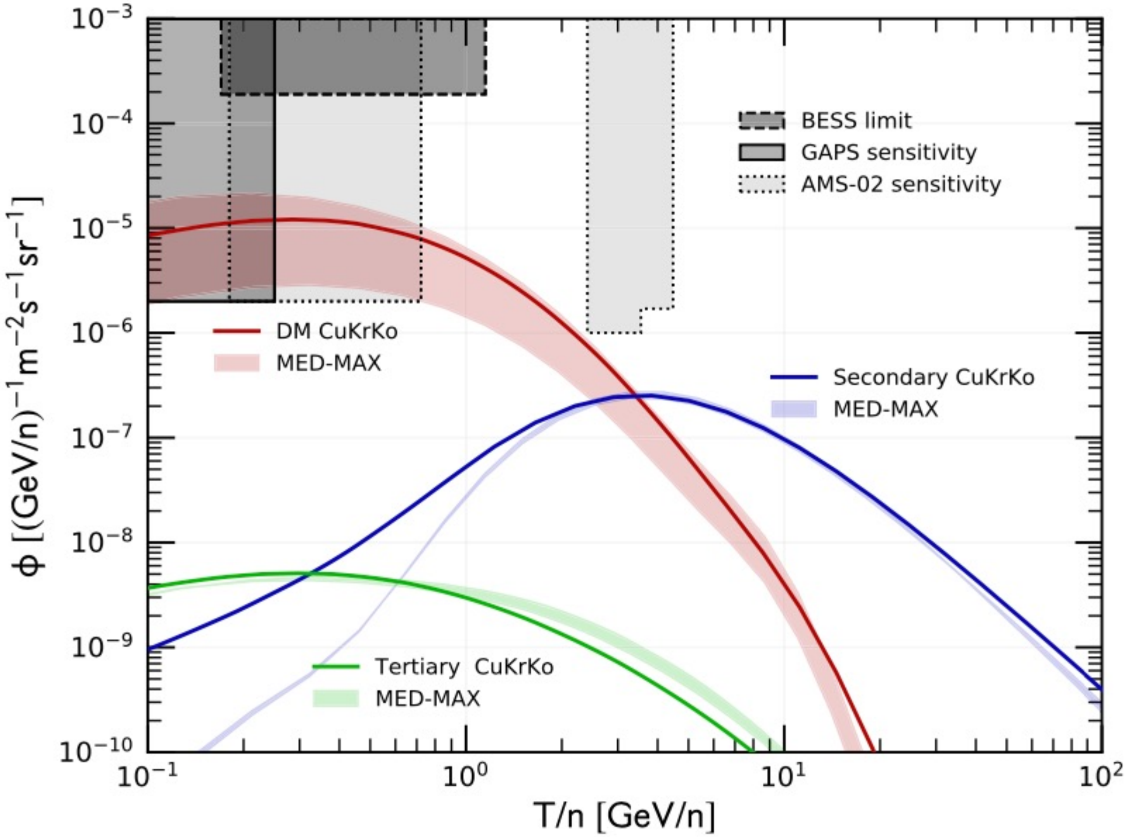
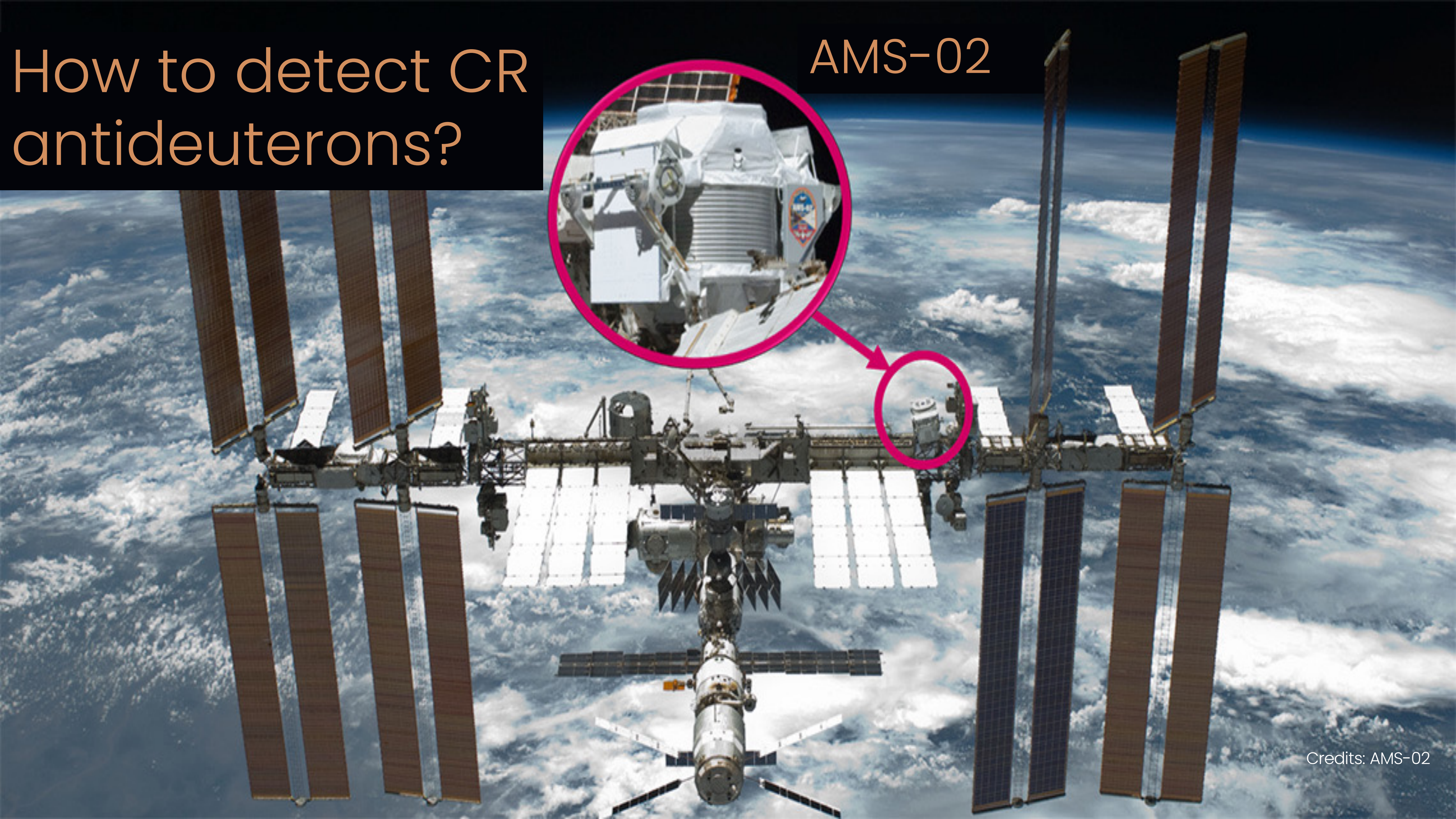
Why studying CR antideuterons?



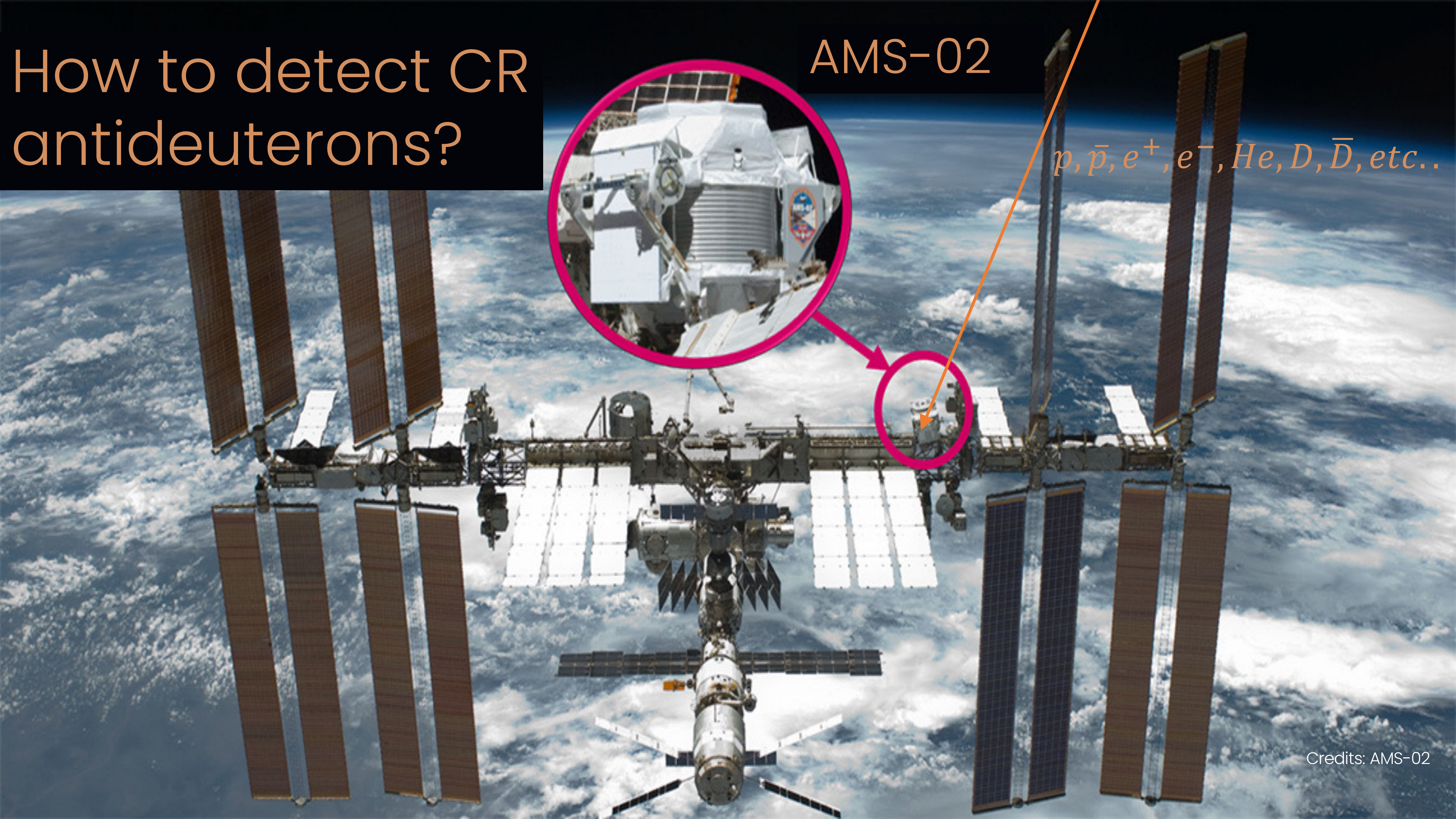
From: Korsmeier et al, Phys. Rev. D 97, 103011 (2018)

- Rare events: less than 10^{-7} of the total CR flux
- Never detected in space
- Sensitive channel for Dark Matter searches (see *Donato et al., 2000; Korsmeier et al. 2018, Serksnyte et al, 2022, …*)

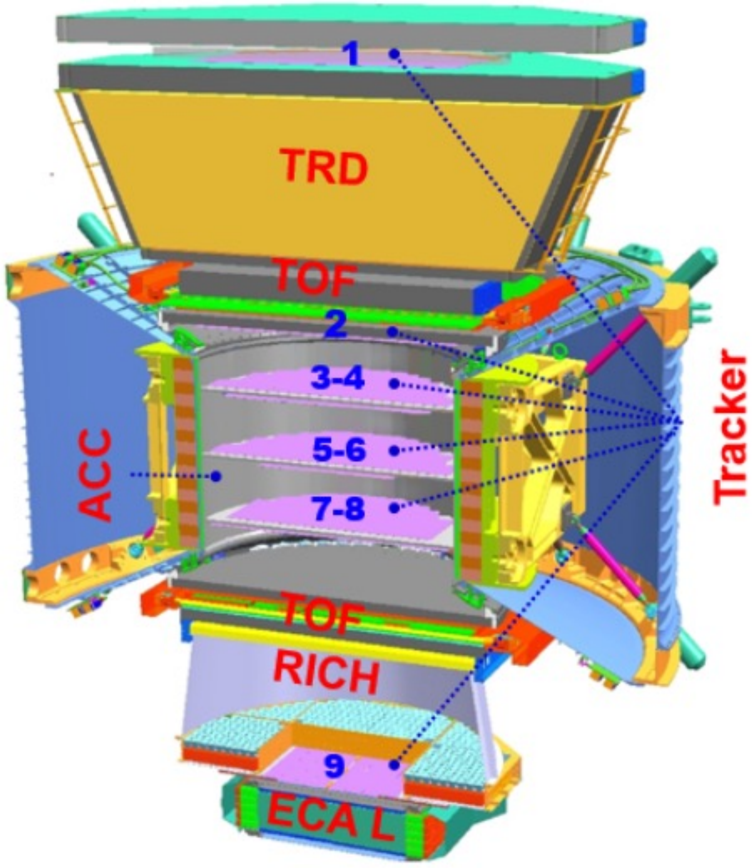
How to detect CR antideuterons?



How to detect CR antideuterons?

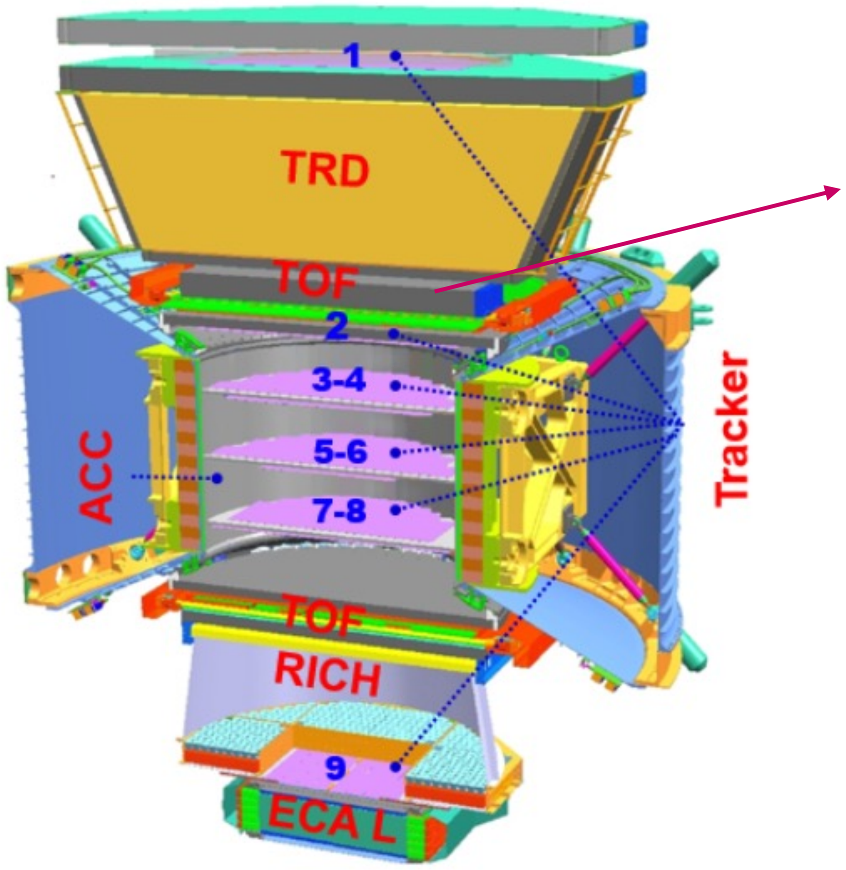


Isotope identification



From: A. Kounine, International Journal of Modern Physics E, 21(8): 1230005, 2012.

Isotope identification



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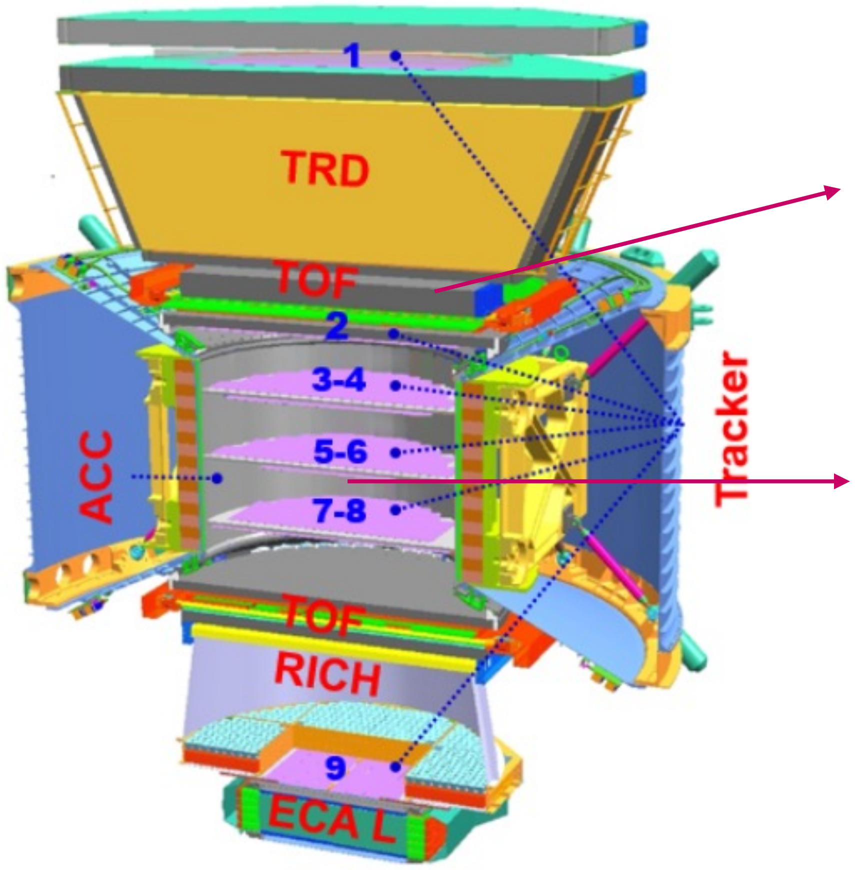
Time of Flight detector:

velocity and charge

Isotope identification



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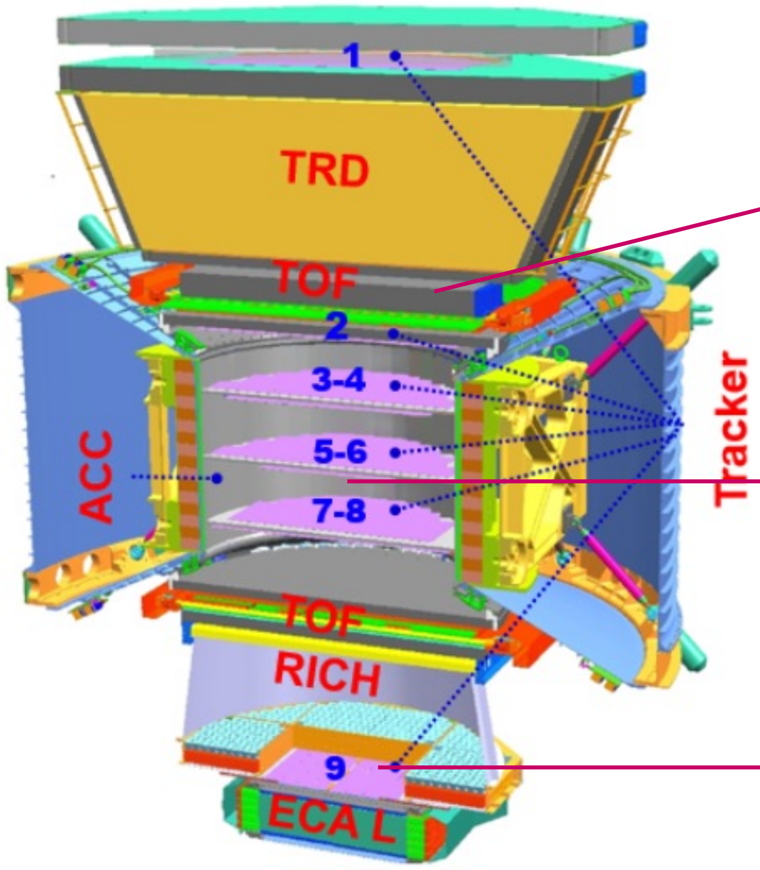
Time of Flight detector:

velocity and charge

Silicon Tracker (Inner):

rigidity, charge sign and charge

Isotope identification



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Time of Flight detector:

velocity and charge

Silicon Tracker (Inner):

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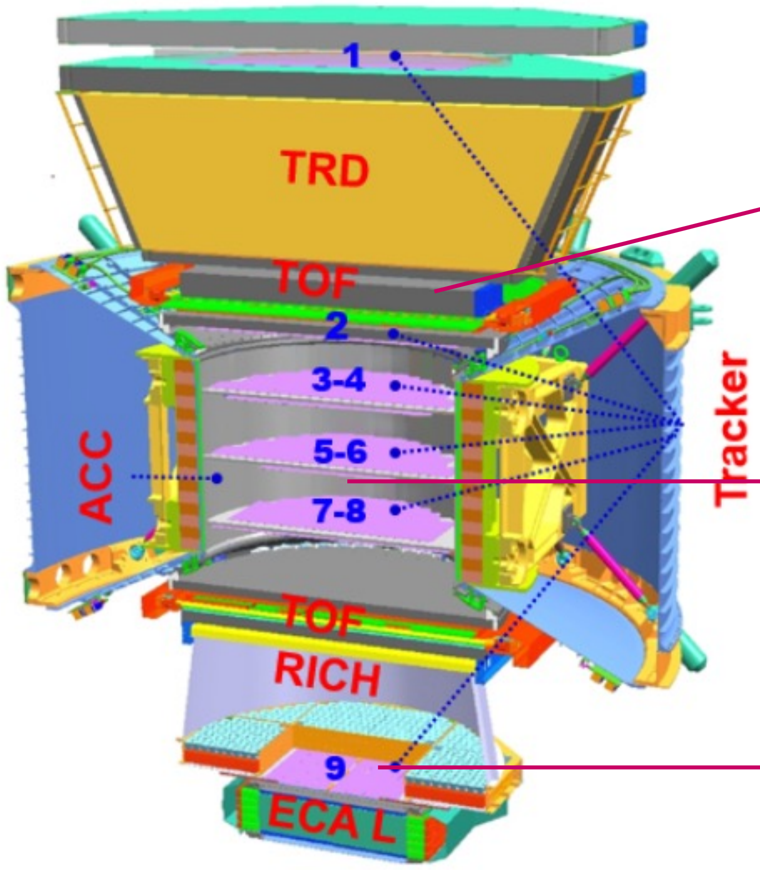
Ring Imaging Cherenkov detector (RICH):

velocity

Isotope identification



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Time of Flight detector:

velocity and charge

Silicon Tracker (Inner):

rigidity, charge sign and charge

Ring Imaging Cherenkov detector (RICH):

velocity

Mass reconstruction

$$M = \frac{RZ\sqrt{1-\beta^2}}{\beta}$$

Antideuteron identification

Event selection

Cut based selection to ensure minum event quality

Antideuteron identification

Event selection

Cut based selection to ensure minum event quality

→

Background rejection

wrong reconstructed velocity (RICH)

+

wrong reconstructed charge sign (Silicon Tracker)

Antideuteron identification

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Cut based selection to ensure minum event quality

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Background rejection

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wrong reconstructed charge sign (Silicon Tracker)

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Antideuteron search

Counting events in the antideuteron mass range

Background rejection method

Background rejection

wrong reconstructed velocity (RICH)

+

wrong reconstructed charge sign (Silicon Tracker)

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Classification task → **Boosted Decision Trees**

Background rejection method

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Classification task → **Boosted Decision Trees**

Input:

- Labeled data (background-like or signal-like)
- set of features

Background rejection method

Background rejection

wrong reconstructed velocity (RICH)

+

wrong reconstructed charge sign (Silicon Tracker)

Classification task → **Boosted Decision Trees**

Input:

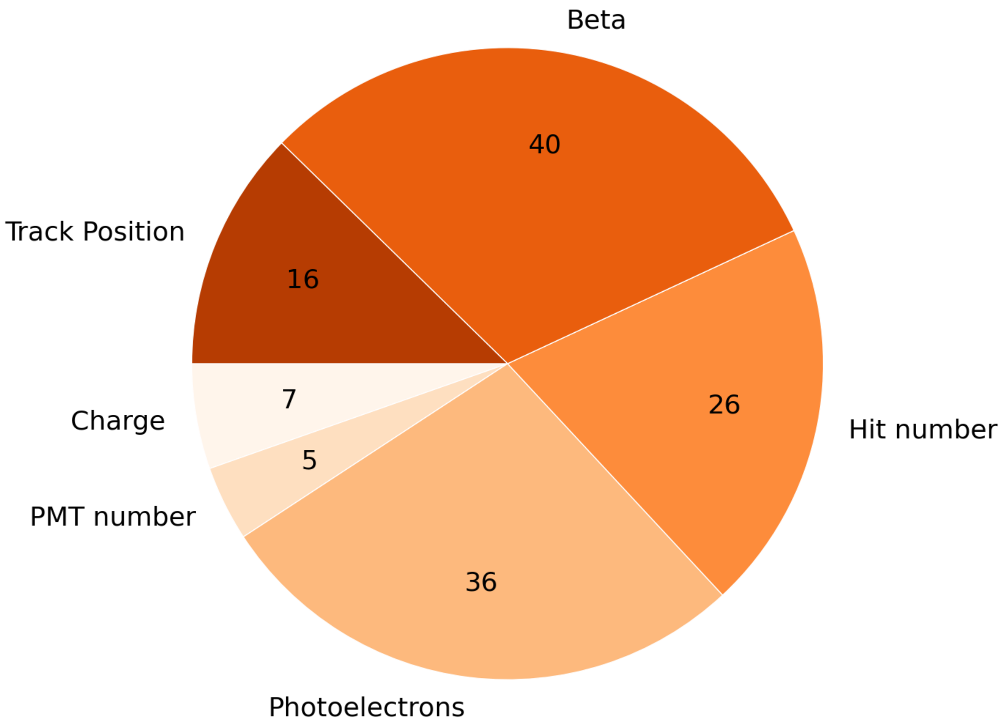
- Labeled data (background-like or signal-like)
- set of features

How to improve isotope identification with AMS-02 using Machine Learning feature selection methods?

Borchiellini et al., Particles 2024, 7(2), 417-434

Dataset

130 RICH features divided into 6 classes



Borchiellini et al., Particles 2024, 7(2), 417-434

Data-driven approach

→ 2 event samples selected mass-wise

- Background-like events
  ($m > 4$ GeV/c^2)
- Signal-like
  (0.75 GeV/$c^2 < m <$ 1.25 GeV/c^2)

Feature selection

Feature selection

Compared different ML feature selection algorithms to a physics-driven approach from *Bueno et al., Nucl. Instrum. Meth. A 2023, 1056, 168644*

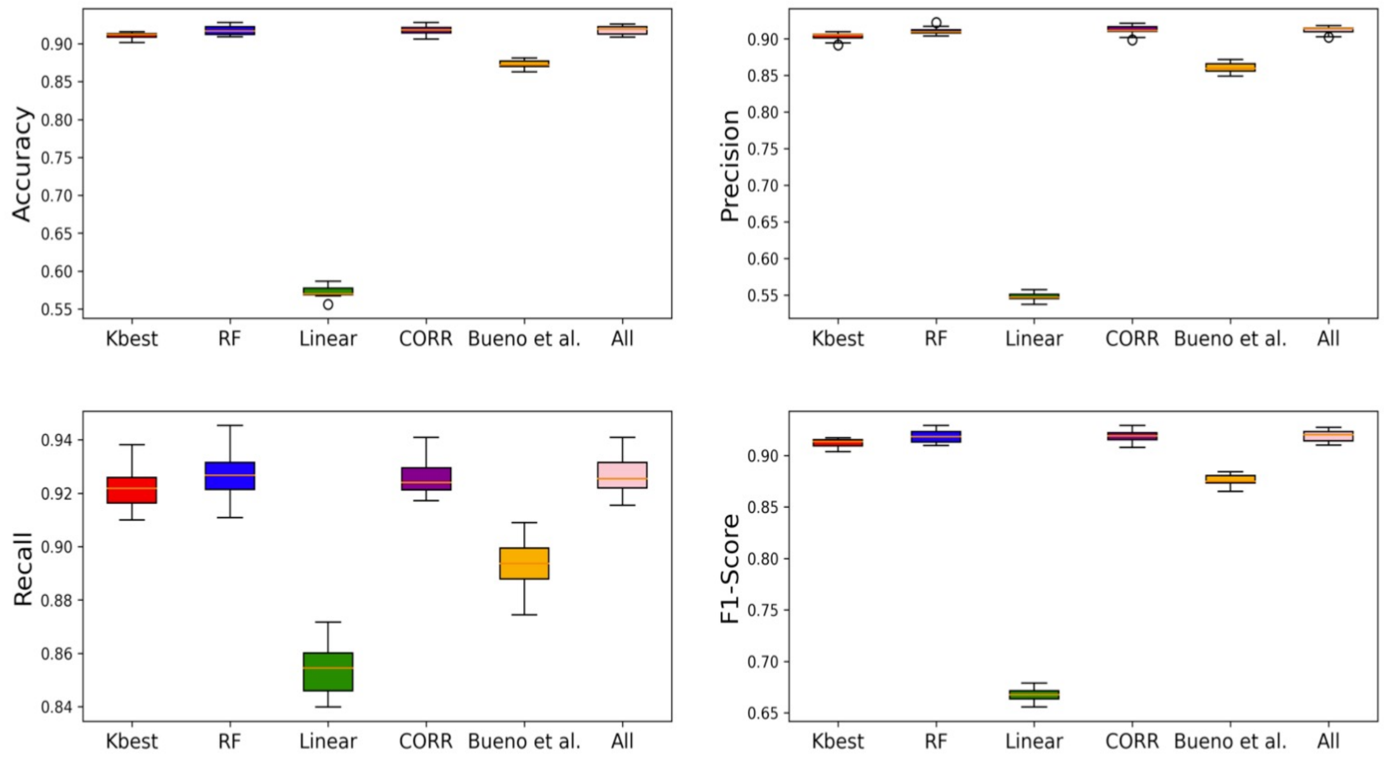
ML feature selection methods used:

- Kbest
- Random Forest
- Linear Regression
- Pearson's Correlation

Performace evaluation

- BDT trained with sets features selected by the different methods
- Performance of feature selection techniques evaluated on the performance of the classifier (accuracy, precision, recall, F1-Score)

Methods performances



Borchiellini et al., Particles 2024, 7(2), 417-434

- Kbest, Random Forest, and correlation outperform the approach described in Bueno et al.
- Random Forest allows for 90% background rejection and 92% signal efficiency

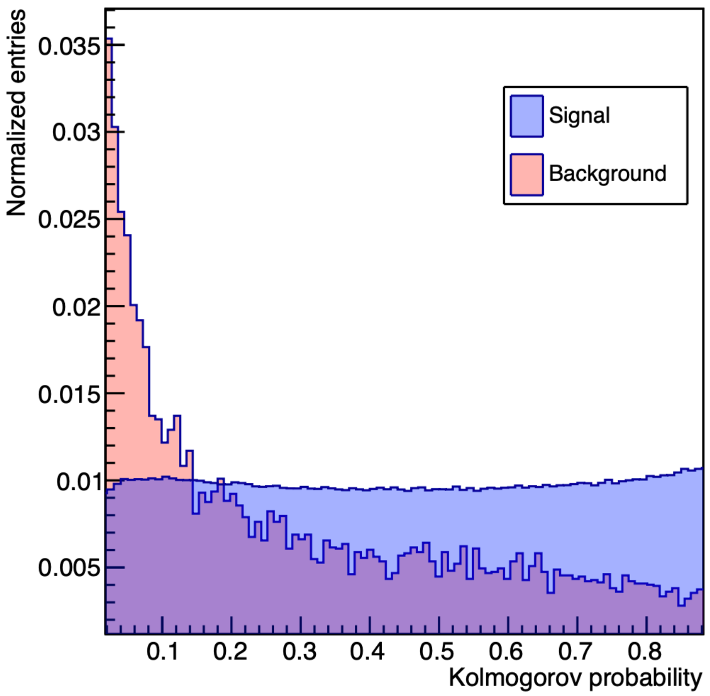
Summary

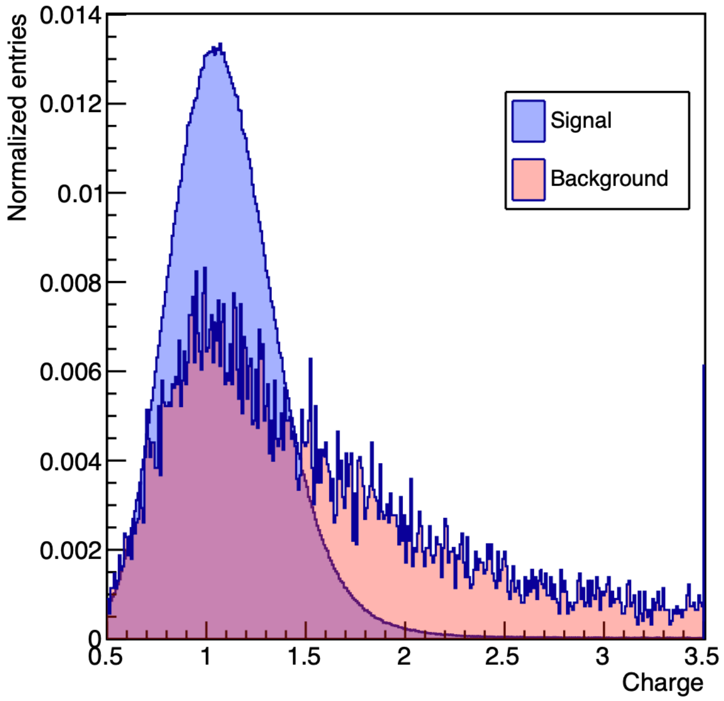
- CR Antideuterons have never been detected in space but they are a sensitive channel for investigating new physics
- An efficient rejection of the background is needed to perform antideuteron identification
- Machine Learning Feature Selection methods improve the performance of the classifier rejecting RICH background

→ For the future: apply ML feature selection techniques to improve efficiency in rejecting charged confused events

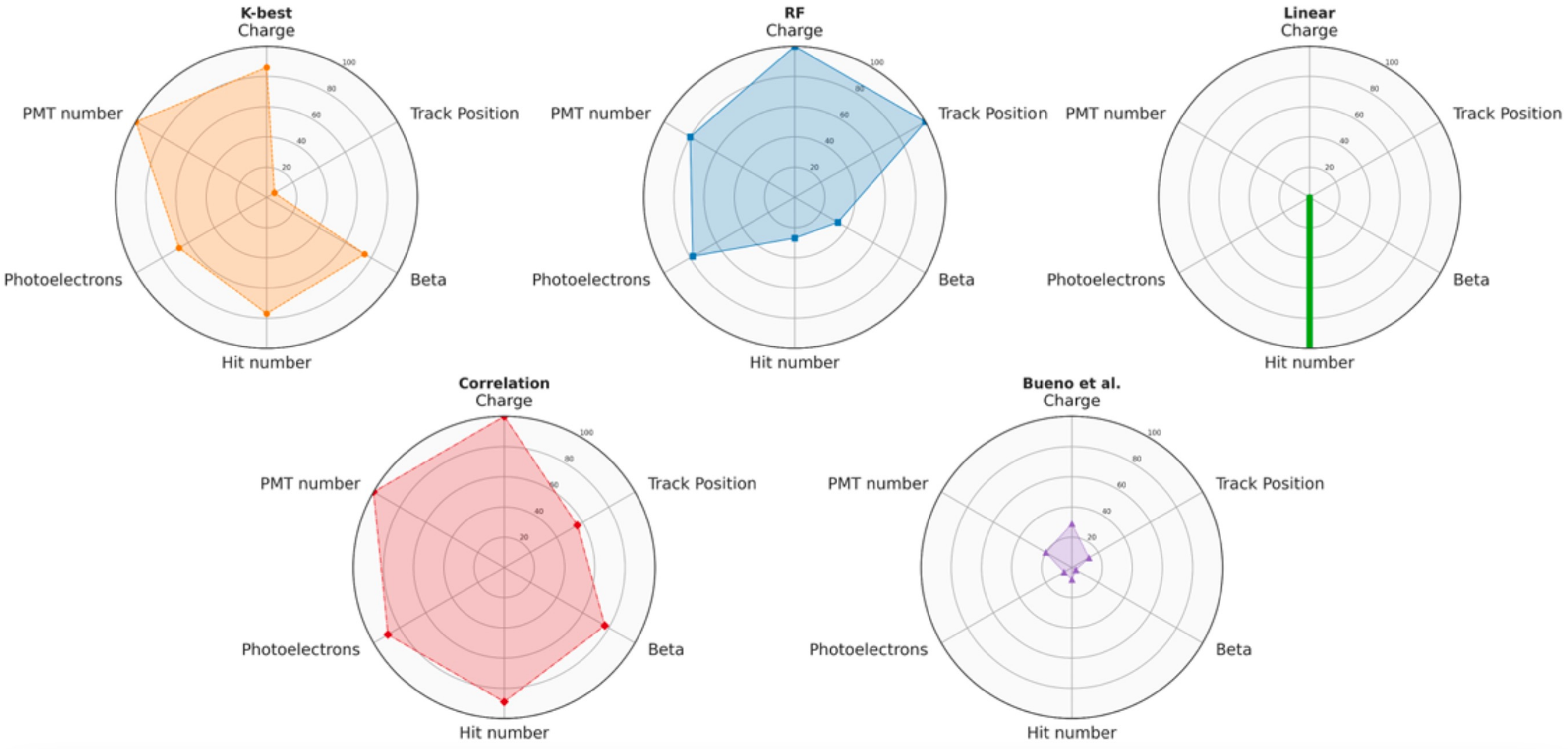
BACKUP

Feature distribution



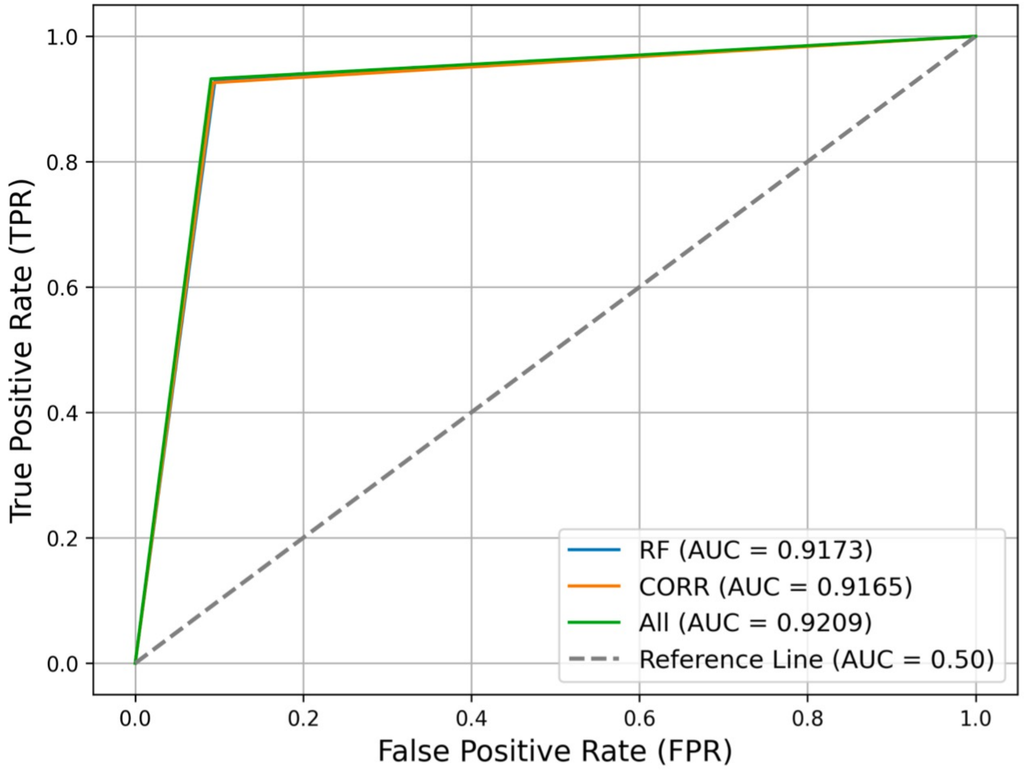


Feature selection



	Charge	Track Position	Beta	Hit Number	Photoelectrons	PMT Number	Total
Kbest	6 (86%)	1 (6%)	30 (75%)	20 (77%)	24 (67%)	5 (100%)	86
RF	7 (100%)	16 (100%)	13 (33%)	7 (27%)	28 (78%)	4 (80%)	75
Linear	0 (0%)	0 (0%)	0 (0%)	1 (100%)	0 (0%)	0 (0%)	1
Correlation	7 (100%)	9 (56%)	31 (77%)	23 (89%)	32 (89%)	5 (100%)	107
Bueno et al.	2 (29%)	2 (13%)	1 (3%)	2 (8%)	2 (6%)	1 (20%)	9

ROC curve


1.0
0.8
0.6
0.4
0.2
0.0
True Positive Rate (TPR)
0.0
0.2
0.4
0.6
0.8
1.0
False Positive Rate (FPR)
RF (AUC = 0.9173)
CORR (AUC = 0.9165)
All (AUC = 0.9209)
Reference Line (AUC = 0.50)

Antideuteron identification

Event selection

Cut based selection to ensure minum event quality

→

Background rejection

reject events with wrongly reconstructed mass

→

Antideuteron search

Counting events in the antideuteron mass range

Background rejection

Background rejection

wrongly reconstructed velocity (RICH)

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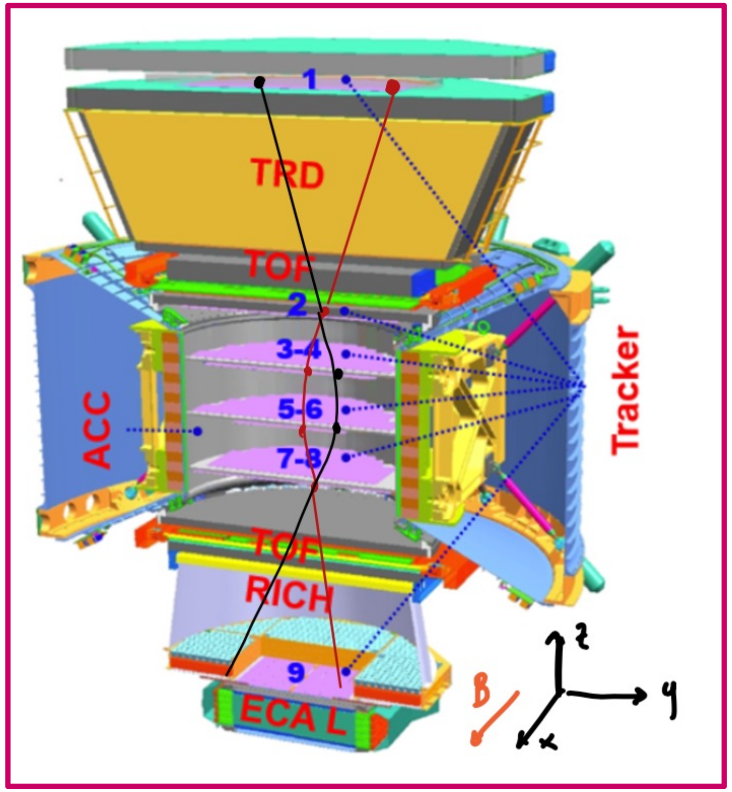
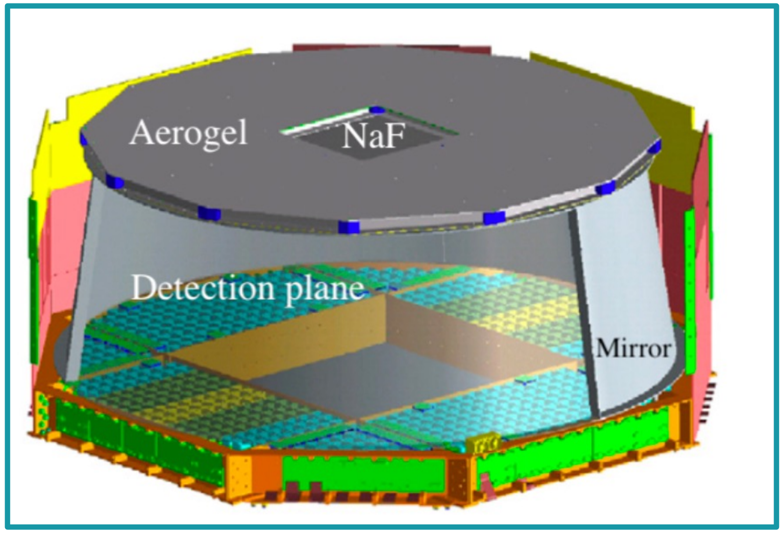
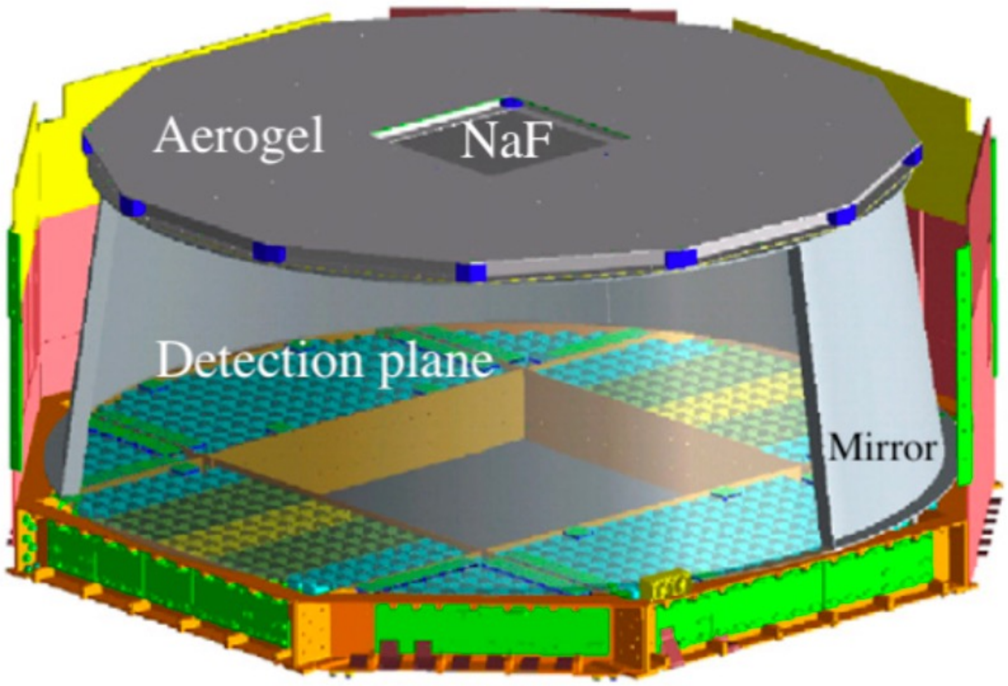
wrongly reconstructed charge sign (Silicon Tracker)





Velocity measurement - RICH



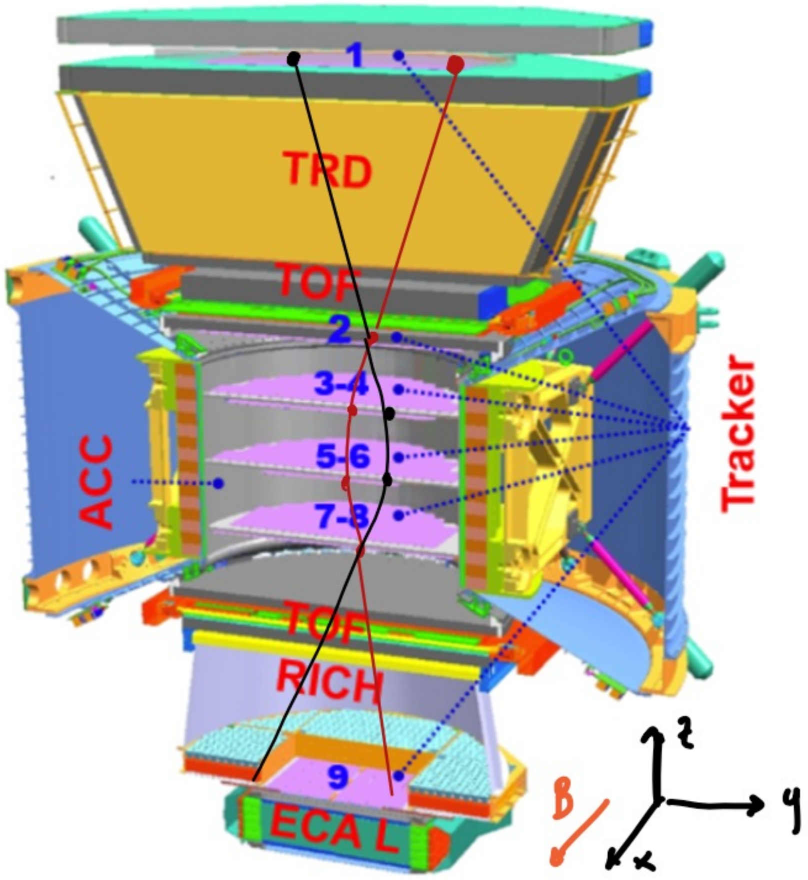
Velocity is reconstructed from the cherenkov angle (from Ring):

$$\beta = \frac{1}{n \cos \theta_c}$$

Number of photons emitted:

$$\frac{d^2 N}{d\lambda dx} = \frac{2\pi}{\lambda^2} \alpha Z^2 \sin^2 \theta_C$$

Rigidity sign measurement - Tracker



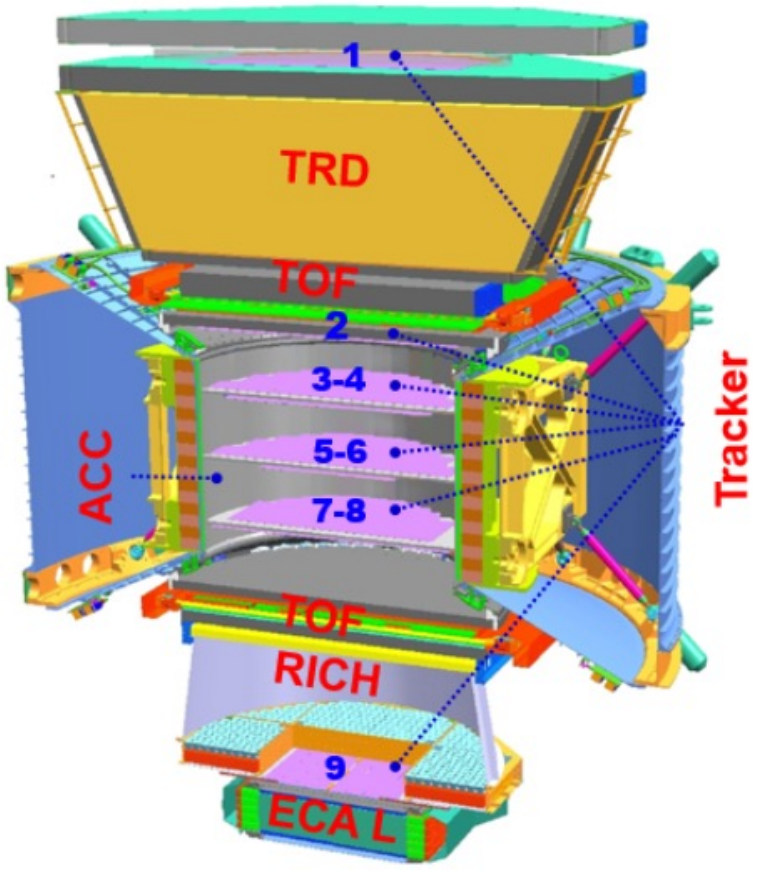
→ Charge confused events

Particles confused for their antimatter counterpart (and viceversa)

2 possible causes for charge confusion:

- Spillover
- Interactions inside Tracker

Challenges



Two main backgrounds to reject:

- Protons with wrongly reconstructed charge sign (charge confusion)
- Particles with wrongly reconstructed RICH velocity