Combined machine learning analysis for $\overline{He}$ search with the AMS-02 experiment

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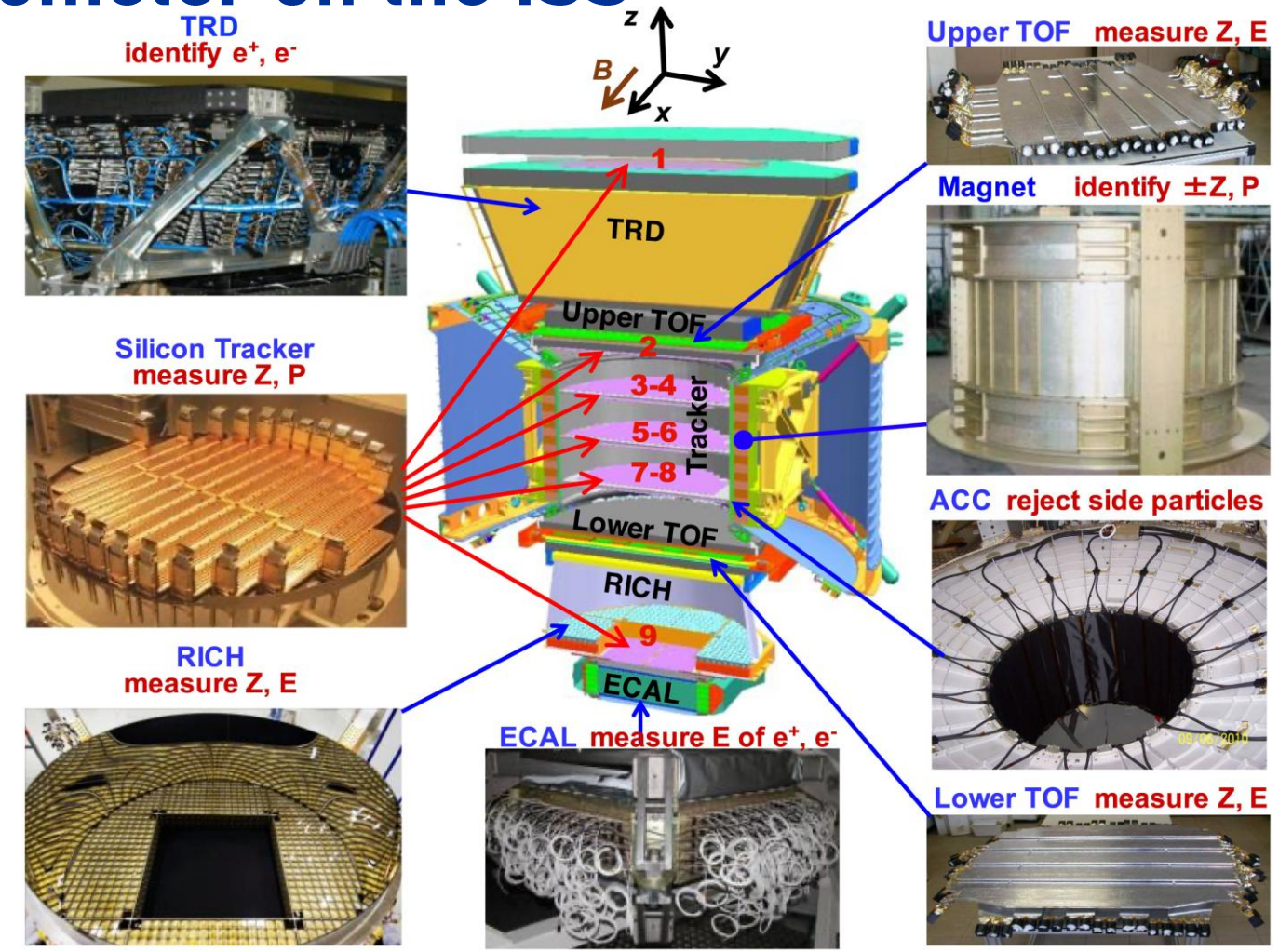
The Alpha Magnetic Spectrometer on the ISS

State-of-the-art particle physics detector:

- Launched on the 16th of May 2011
- Measures the flux of CRs components

Main goals:

- **Complex antimatter** such as $\bar{d}$ and $\overline{He}$
- Indirect DM detection through e^+ and $\bar{p}$
- Production, acceleration and propagation of CRs
- Short and long-term effect of solar activity on CRs fluxes



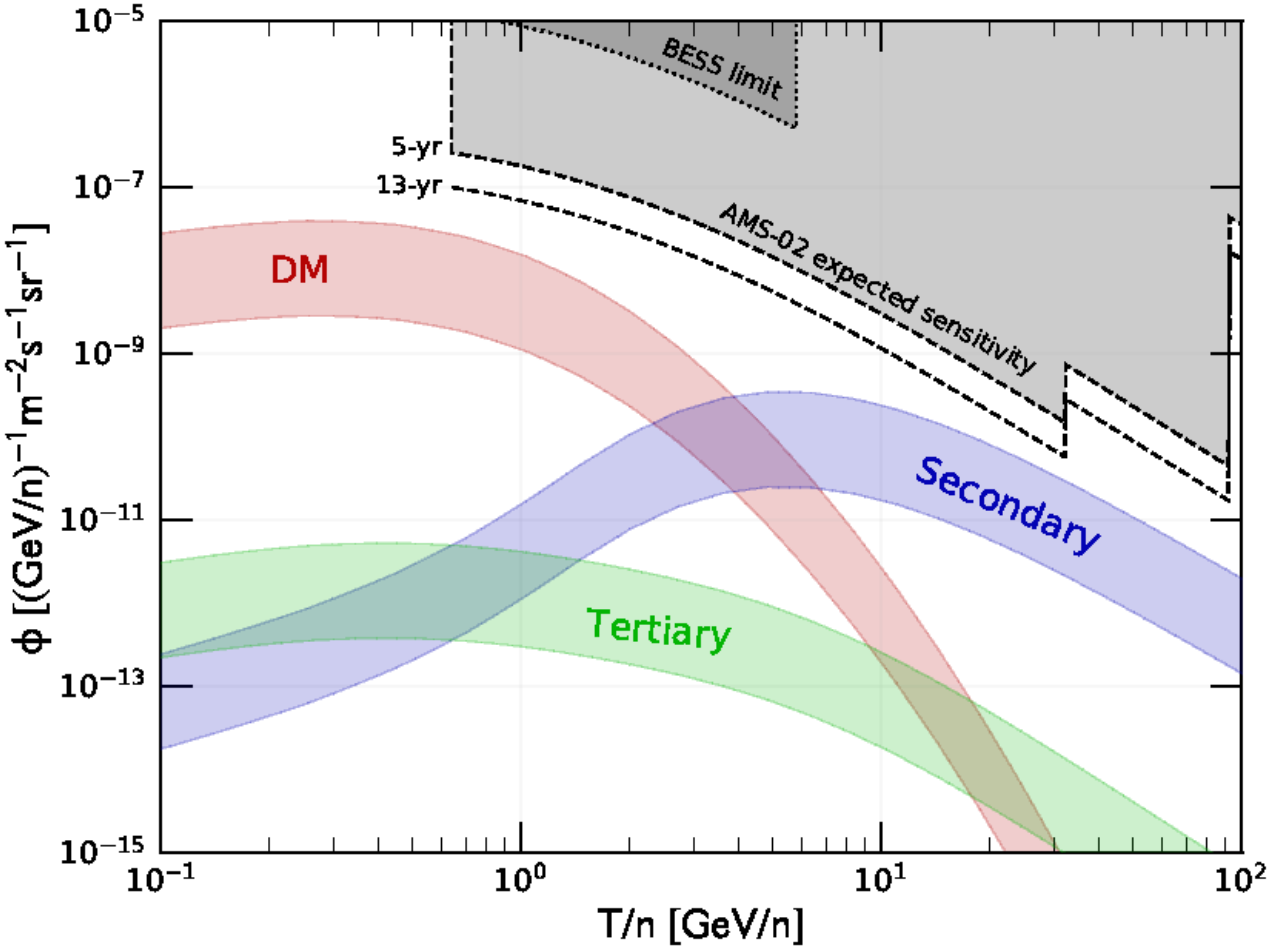
The rationale

Why is the first detection of $\overline{He}$ among CRs interesting?

- New insight into Matter-antimatter imbalance
- Big Bang Nucleosynthesis
- Possibly related to new physics as **dark matter** interactions, or to a **primordial origin**.

$\overline{He}$ has a negligible astrophysical background (at low T/n [GeV/n].

Only a magnetic spectrometer can resolve the charge sign.

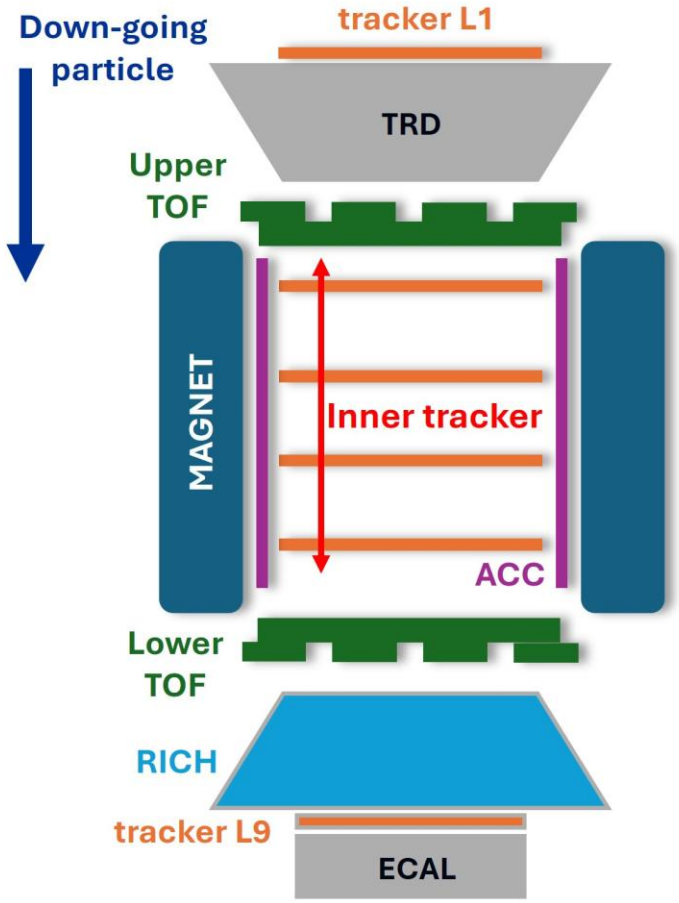


Event selection

AMS can search for $\overline{He}$, looking at the following events:

- downgoing ($\beta_{TOF} > 0$)
- $|Z| = 2$ (TRK+TOF)
- $R_{rec,} < 0$ (TRK)
- β (TOF + RICH)

Reliable $\overline{He}$ candidats should have a reconstructed mass compatible with helium.



	He	$\overline{He}$
TRD		
TOF		
TRK		
ACC		
RICH		
ECAL		

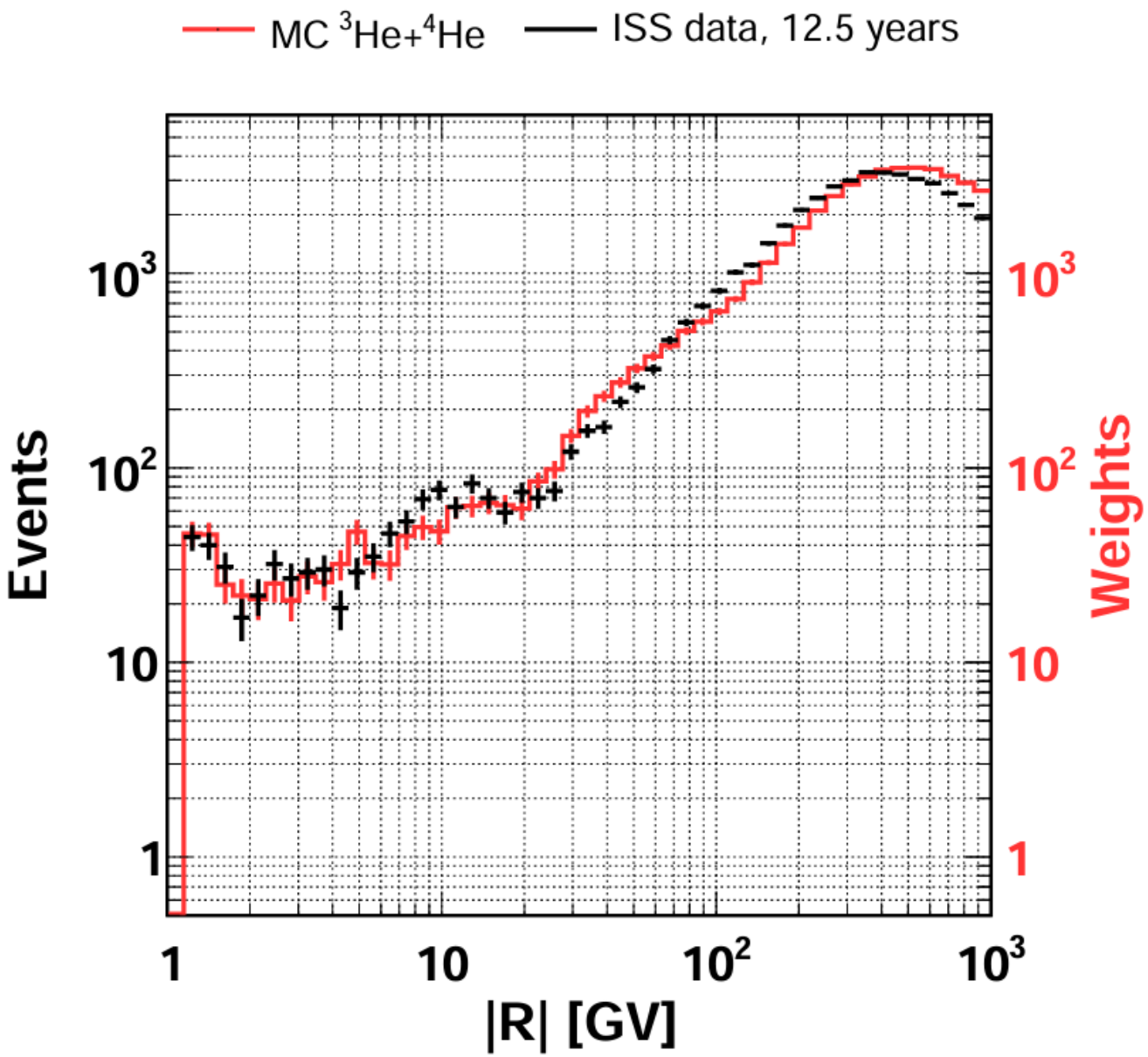
Expected backgrounds

- 2.4×10^9 helium events
- 5.7×10^4 events with $R < 0$

The majority of these events are He nuclei charged confused as $\overline{He}$:

- **Spillover**:
  - Stochastic process, (TRK resolution).
  - Dominant at $R \gtrsim MDR^*$
- Interactions inside the detector:
  - **$^4He \rightarrow {}^3He$ inelastic interaction**
  - **Large angle scattering**
  - Relevant at $R\ [GV] \in [1, MDR]$

Any possible signal lies below a considerable background.



Analysis strategy on ^{3+4}He Monte Carlo

- **Two networks:** one classifier (CL_{MC}) and one autoencoder (AE_{MC}).
  - **trained on ^{4}He, ^{3}He MC (R>0),** tested on MC (R<0).
  - Performances study and debugging.

- **Networks trained on MC are not used on ISS data**: avoiding data-MC disagreement effects.
- **Estimate background contribution** due to charged confused He.

Analysis strategy on ISS data

- **Two networks:** one classifier (CL_{ISS}) and one autoencoder (AE_{ISS}).
  - **trained on ISS data (R>0),** tested on ISS (R<0).

- **Models trained on ISS** are used to **identify possible $\overline{He}$ candidates.**
  - Number of candidates as function of the selection on the network's outputs.

The reconstructed mass of the remaining events **is used as final check.**

Supervised classifier

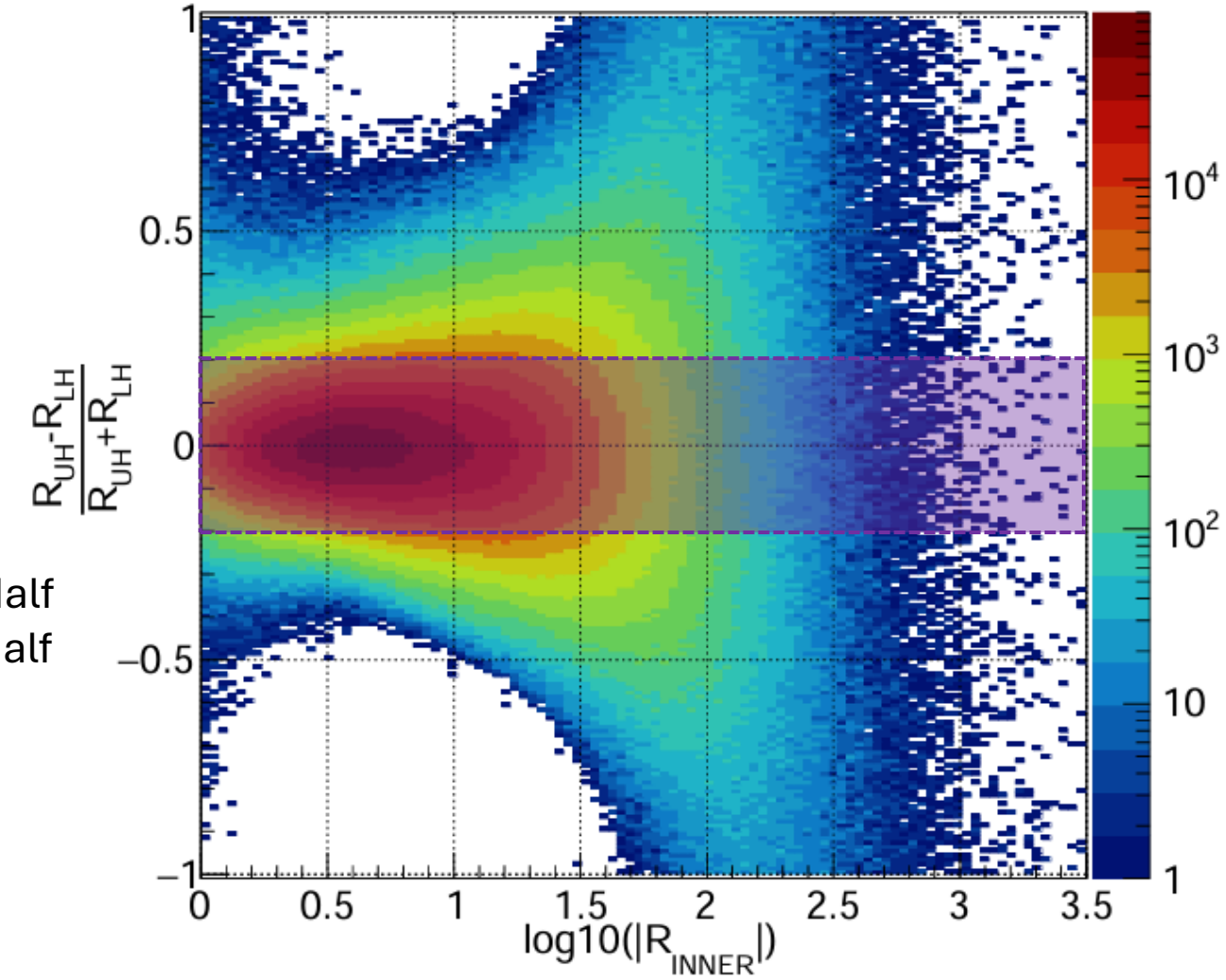
ISS data $R_{INNER} > 0$

- Goal: **distinguish well-reconstructed rigidities from poorly reconstructed ones**.
- The majority of R < 0 events are poorly reconstructed.
- Define a data-driven label:
  - **Based on*** $\frac{R_{UH}-R_{LH}}{R_{UH}+R_{LH}}$
  - sensitive to spillover.

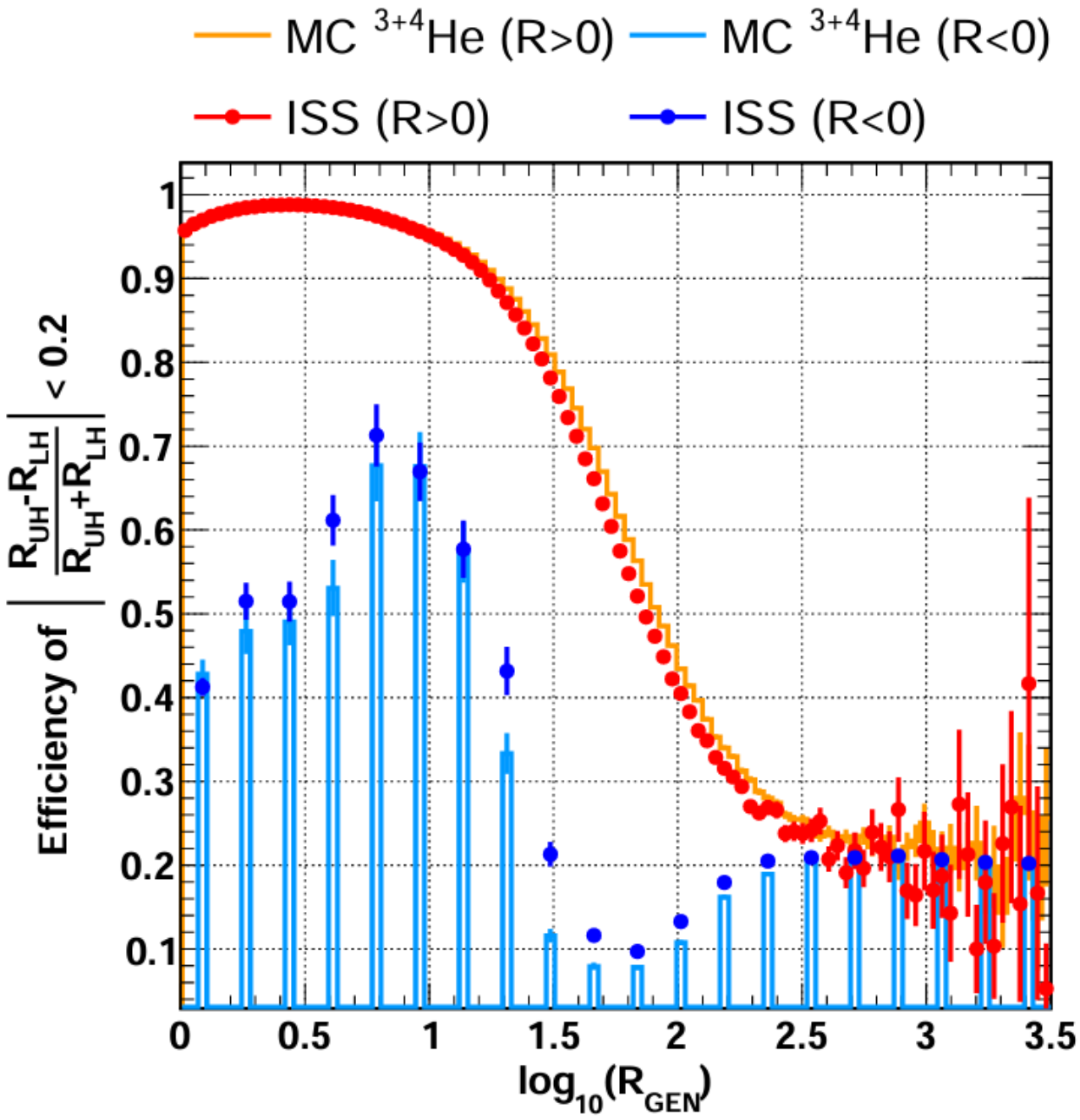
* R_{UH} = Inner Upper Half
R_{LH} = Inner Lower Half

Reliable $\overline{He}$ candidates should have a (CL_{ISS}) score ~ 1.

Well-reconstructed rigidities



Signal efficiency as a function of measured rigidity



Unsupervised autoencoder

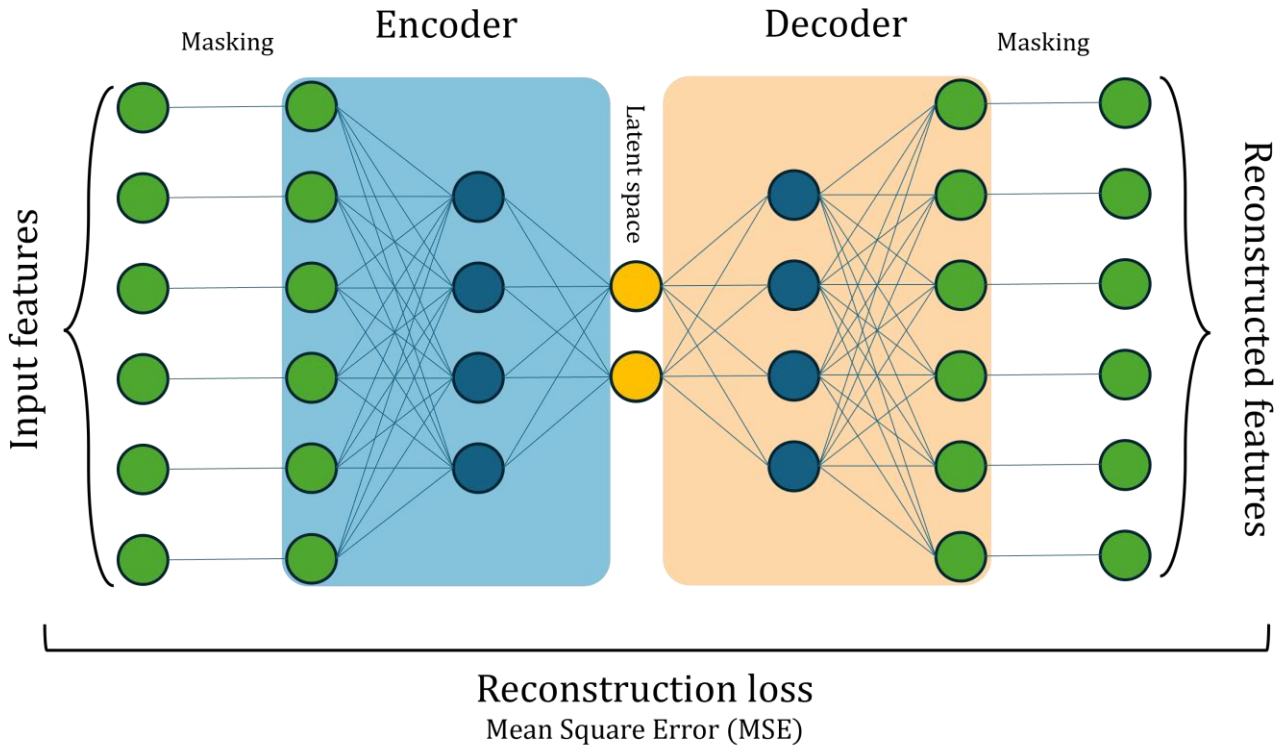
Goal: **minimise losses in the compression-decompression process.**

- $\text{MSE} = \frac{(\boldsymbol{X}-\boldsymbol{Y})^2}{N_{features}}$

$\boldsymbol{X}$ = input
$\boldsymbol{Y}$ = AE's output

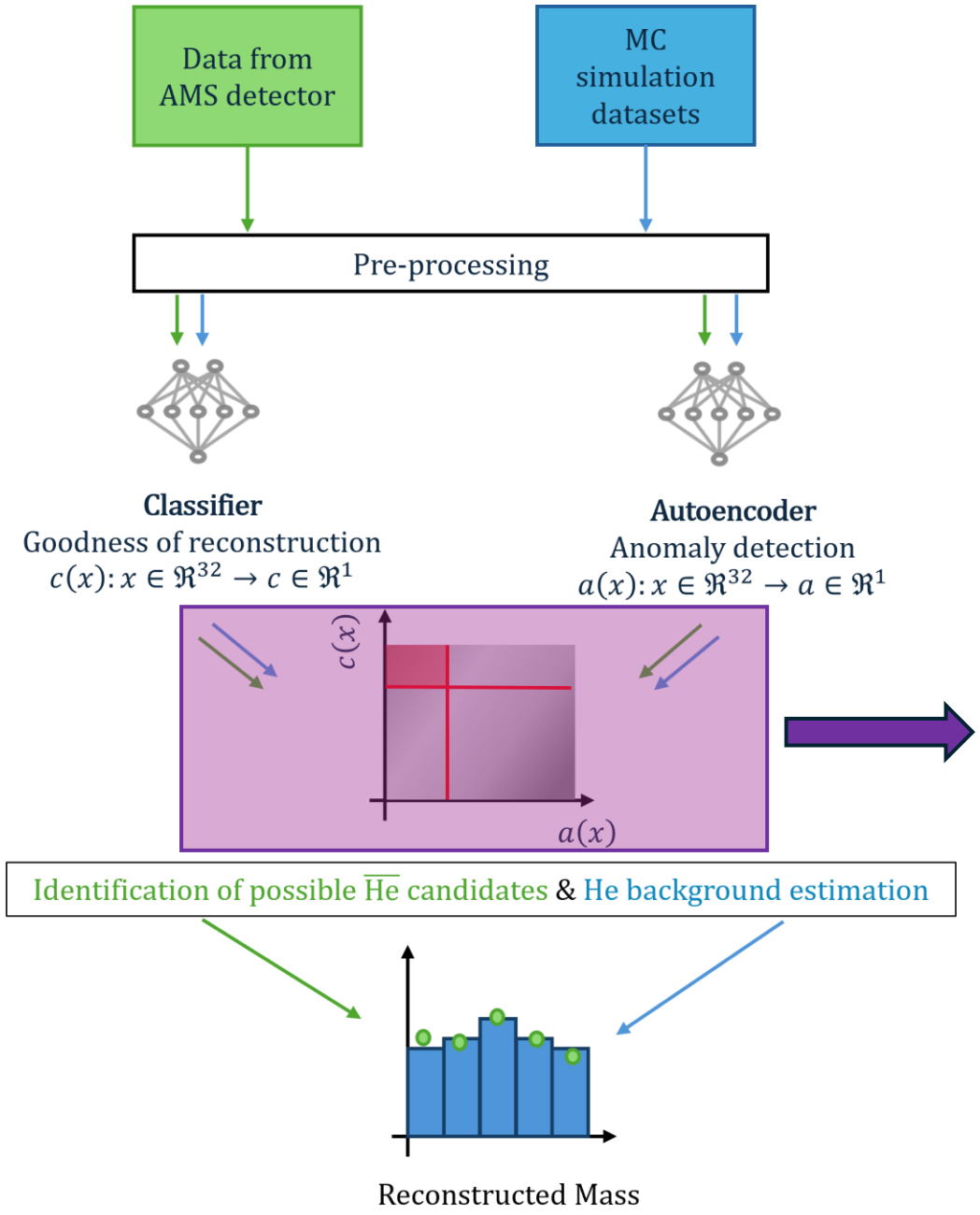
- Well-reconstructed events dominate the R>0 sample.
- Poorly reconstructed events dominate the R<0 sample.

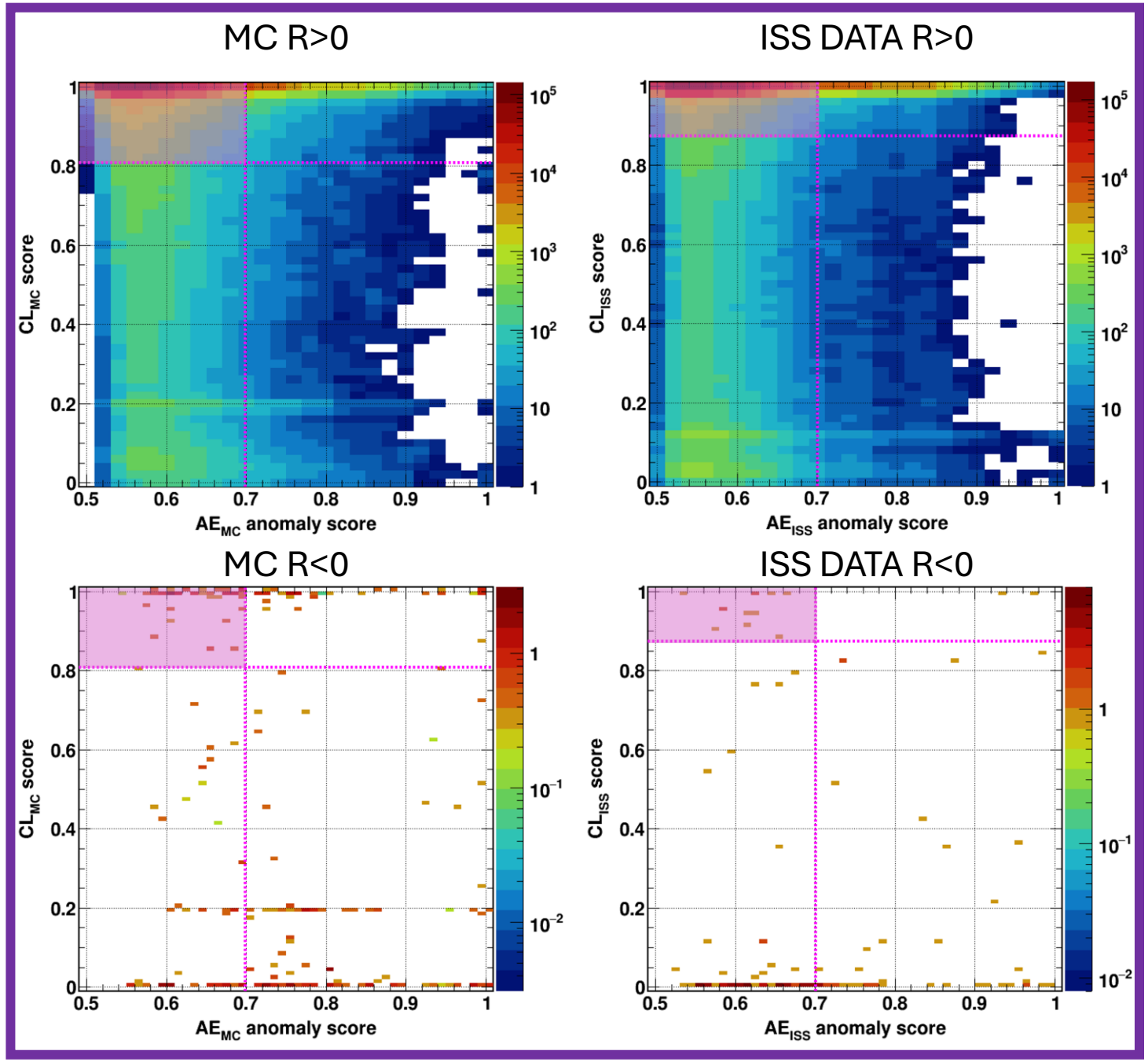
The autoencoder fails on badly reconstructed events, while well-reconstructed events are unaffected.

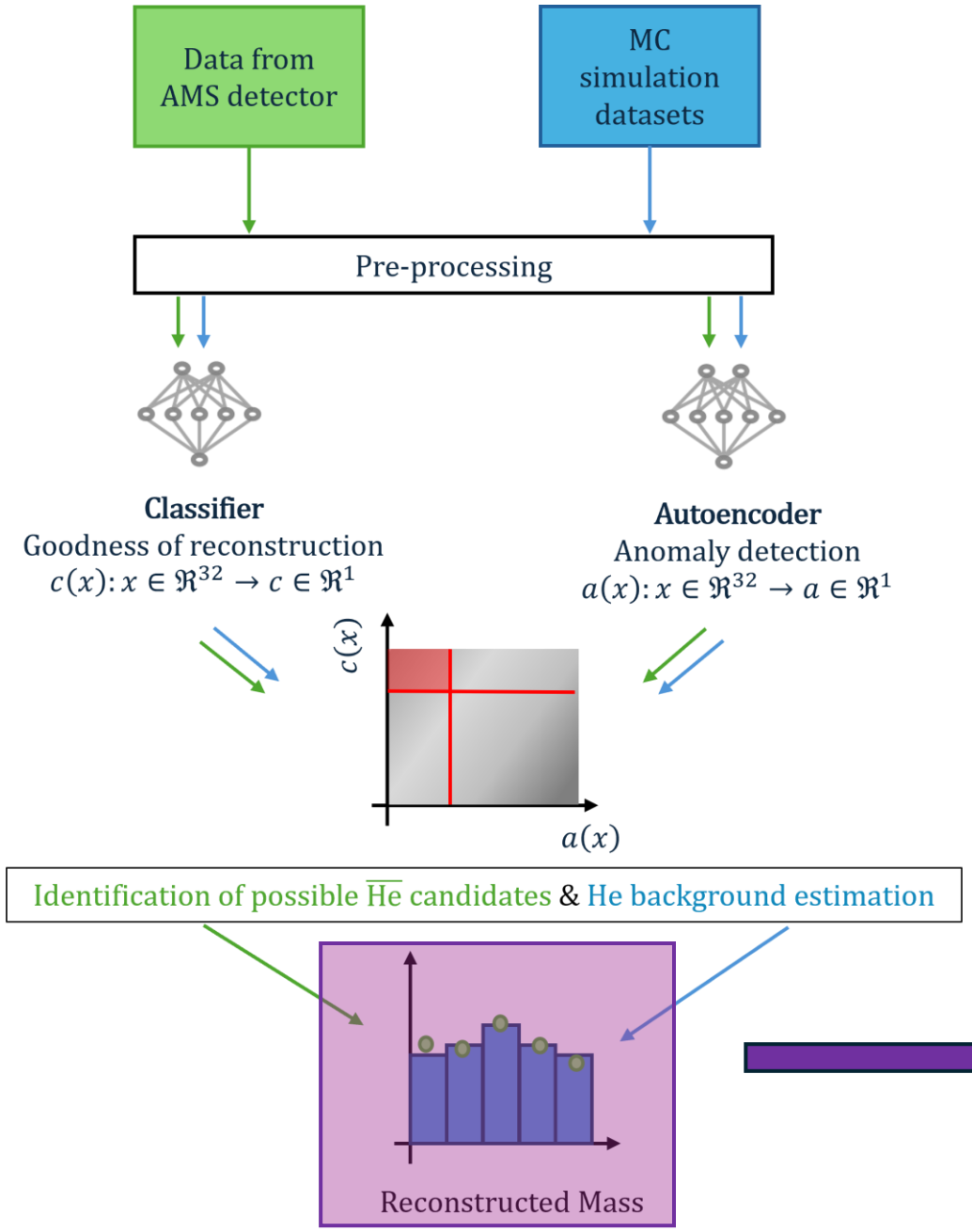


$$\textbf{Anomaly score} = \frac{1}{1+e^{-MSE}} \in [0.5, 1]$$

Reliable $\overline{He}$ candidates should have an anomaly score ~ 0.5.


Data from AMS detector
MC simulation datasets
Pre-processing
Classifier
Goodness of reconstruction
$c(x): x \in \Re^{32} \rightarrow c \in \Re^{1}$
Autoencoder
Anomaly detection
$a(x): x \in \Re^{32} \rightarrow a \in \Re^{1}$
$c(x)$
$a(x)$
Identification of possible $\overline{\text{He}}$ candidates & He background estimation
Reconstructed Mass


MC R>0
ISS DATA R>0
MC R<0
ISS DATA R<0
CL_{MC} score
CL_{ISS} score
AE_{MC} anomaly score
AE_{ISS} anomaly score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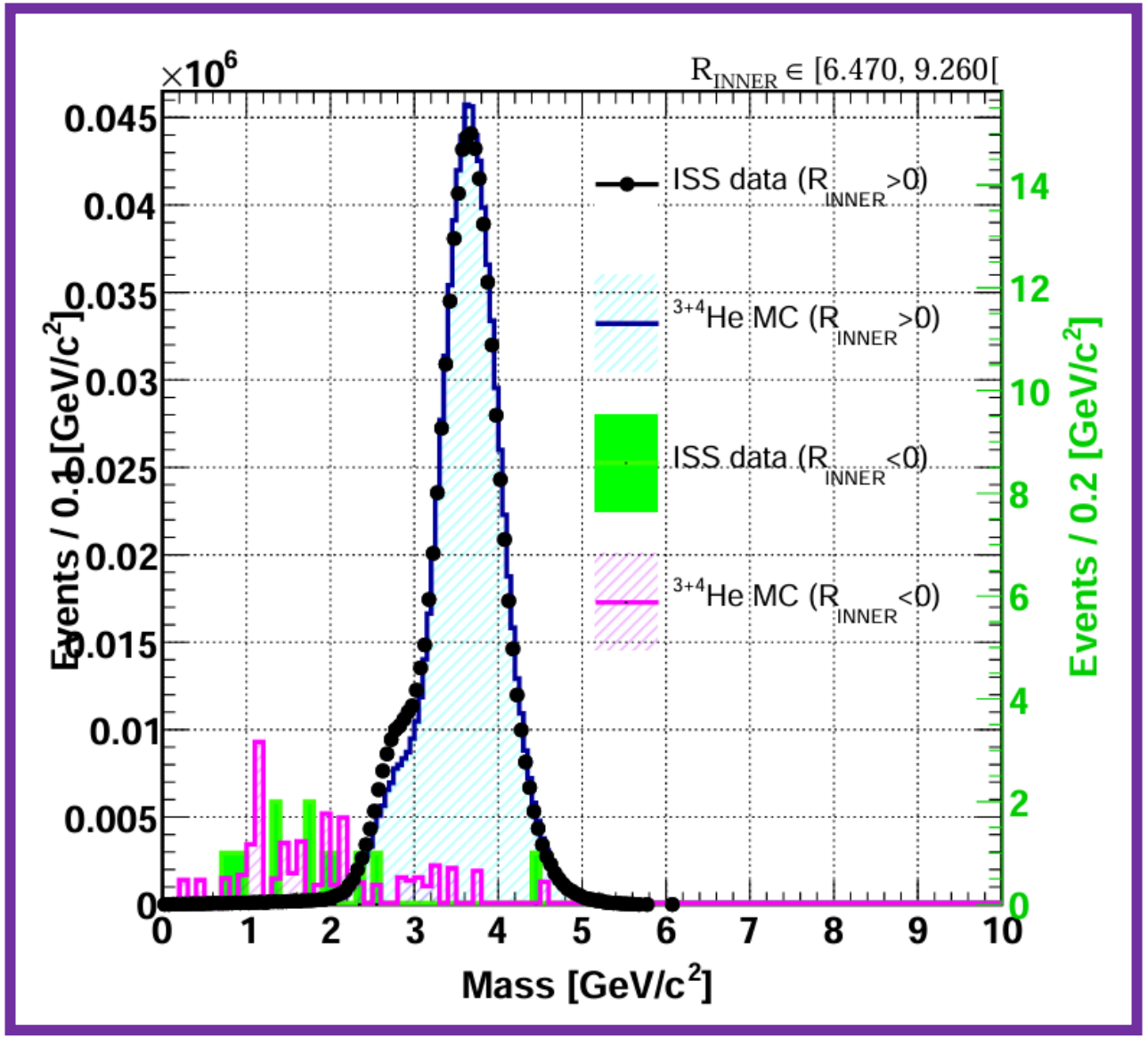

$\times 10^6$
$R_{INNER} \in [6.470, 9.260[$
ISS data (R_{INNER}>0)
$^{3+4}$He MC (R_{INNER}>0)
ISS data (R_{INNER}<0)
$^{3+4}$He MC (R_{INNER}<0)
Events / 0.1 [GeV/c^2]
Events / 0.2 [GeV/c^2]
Mass [GeV/c^2]

CLs method

Do we observe any deviation from the sole background hypothesis?

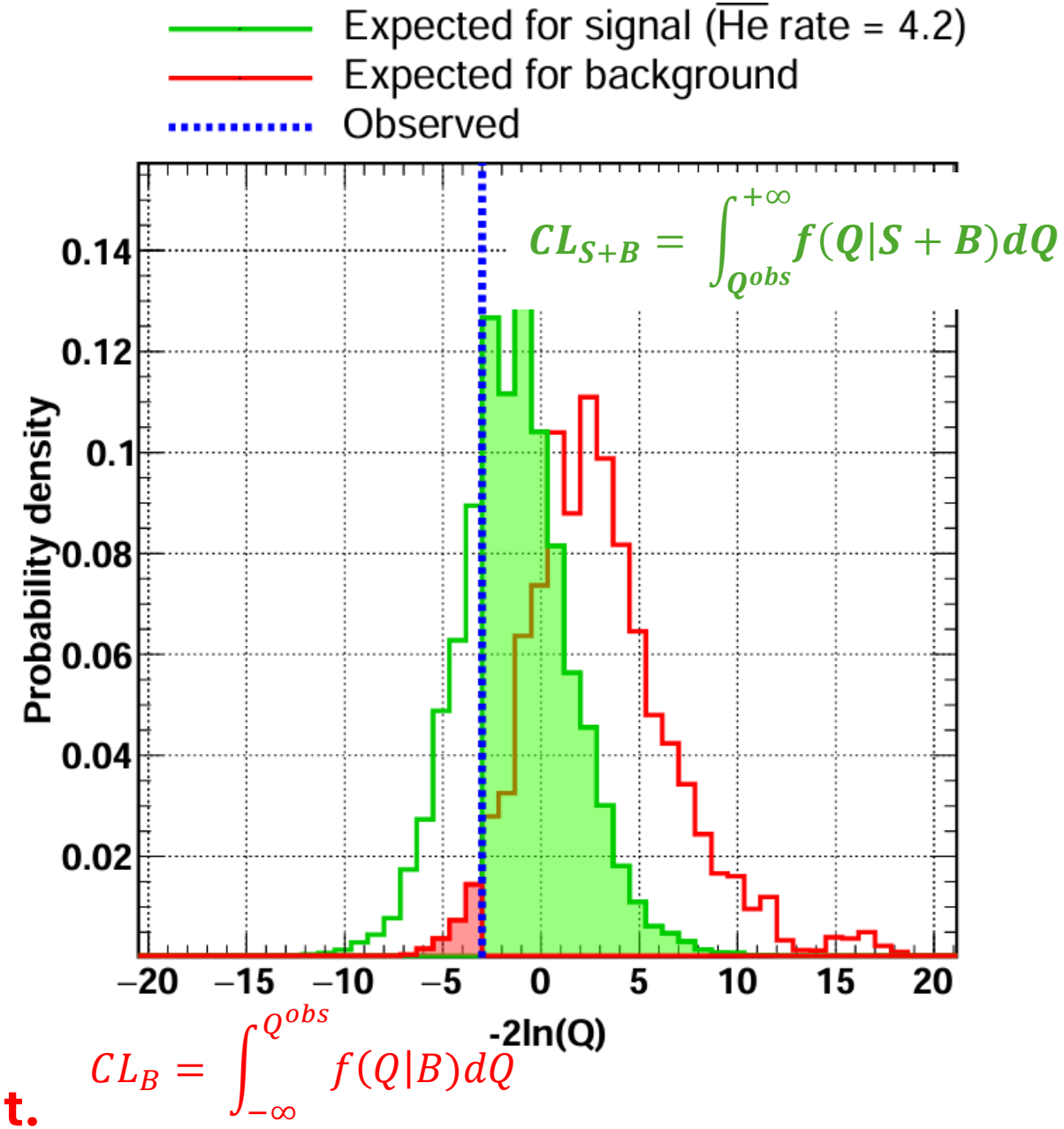
Test statistic: $Q = -2\,ln\left(\frac{L_{S+B}}{L_B}\right)$

- $L(s,b) = \frac{(s+b)^N}{N!}e^{-(s+b)} \cdot \frac{(\tau b)^M}{M!}e^{-\tau b}$
  - $s = \overline{He}$ rate (POI) , b = background rate
  - b, constrained by the helium MC

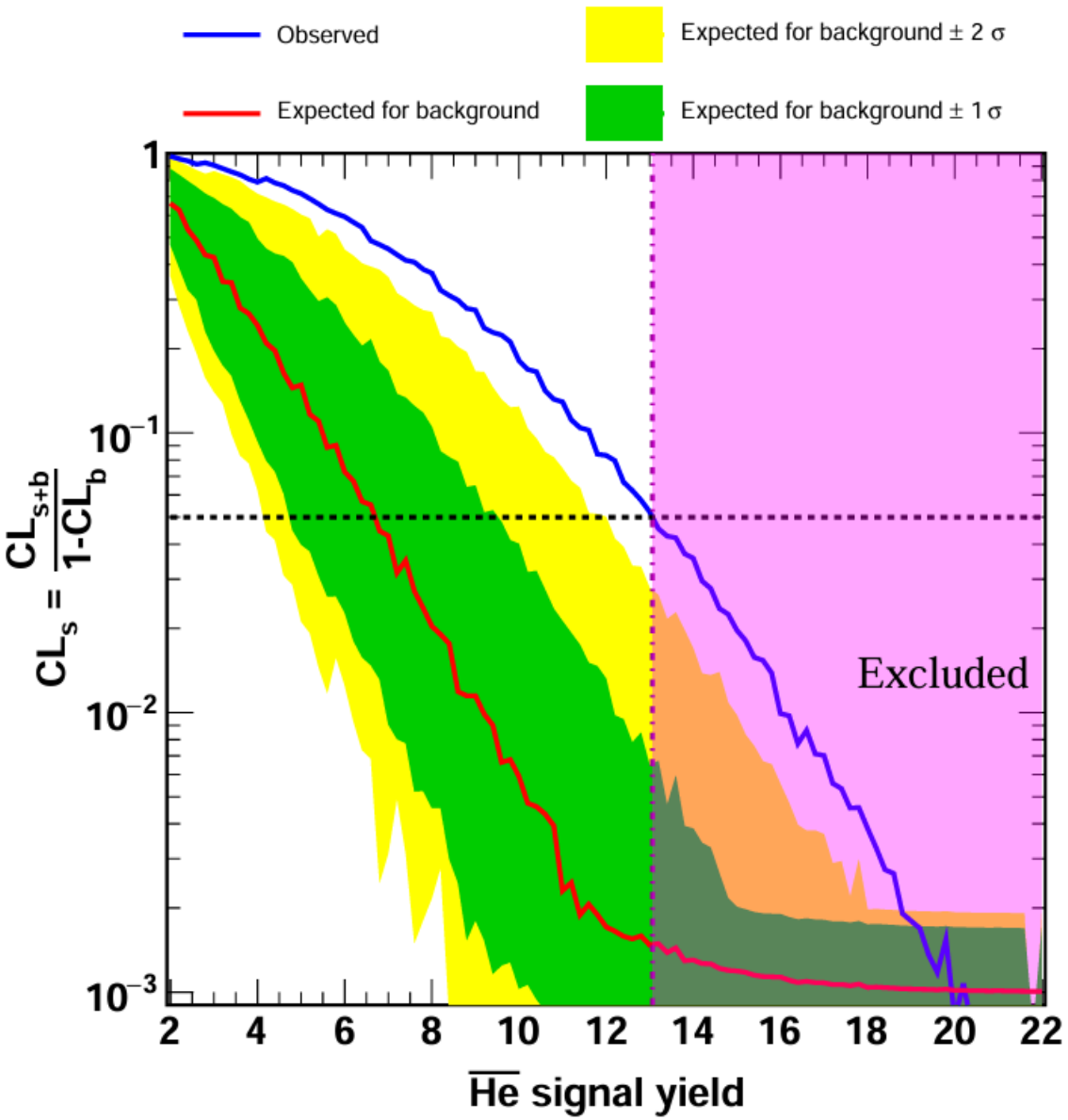
The final decision is taken looking at:

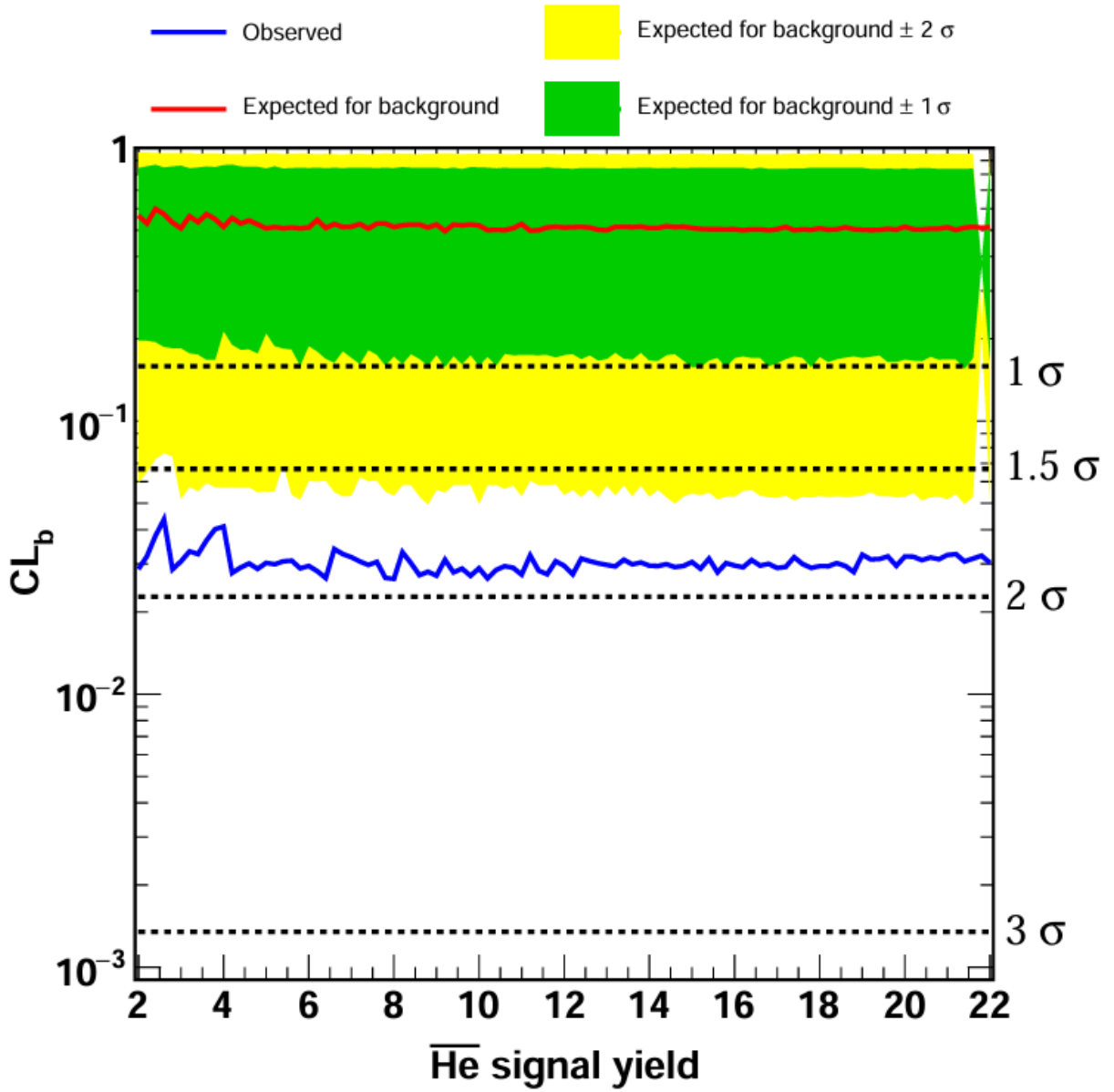
$$CL_s = \frac{CL_{S+B}}{1 - CL_B}$$

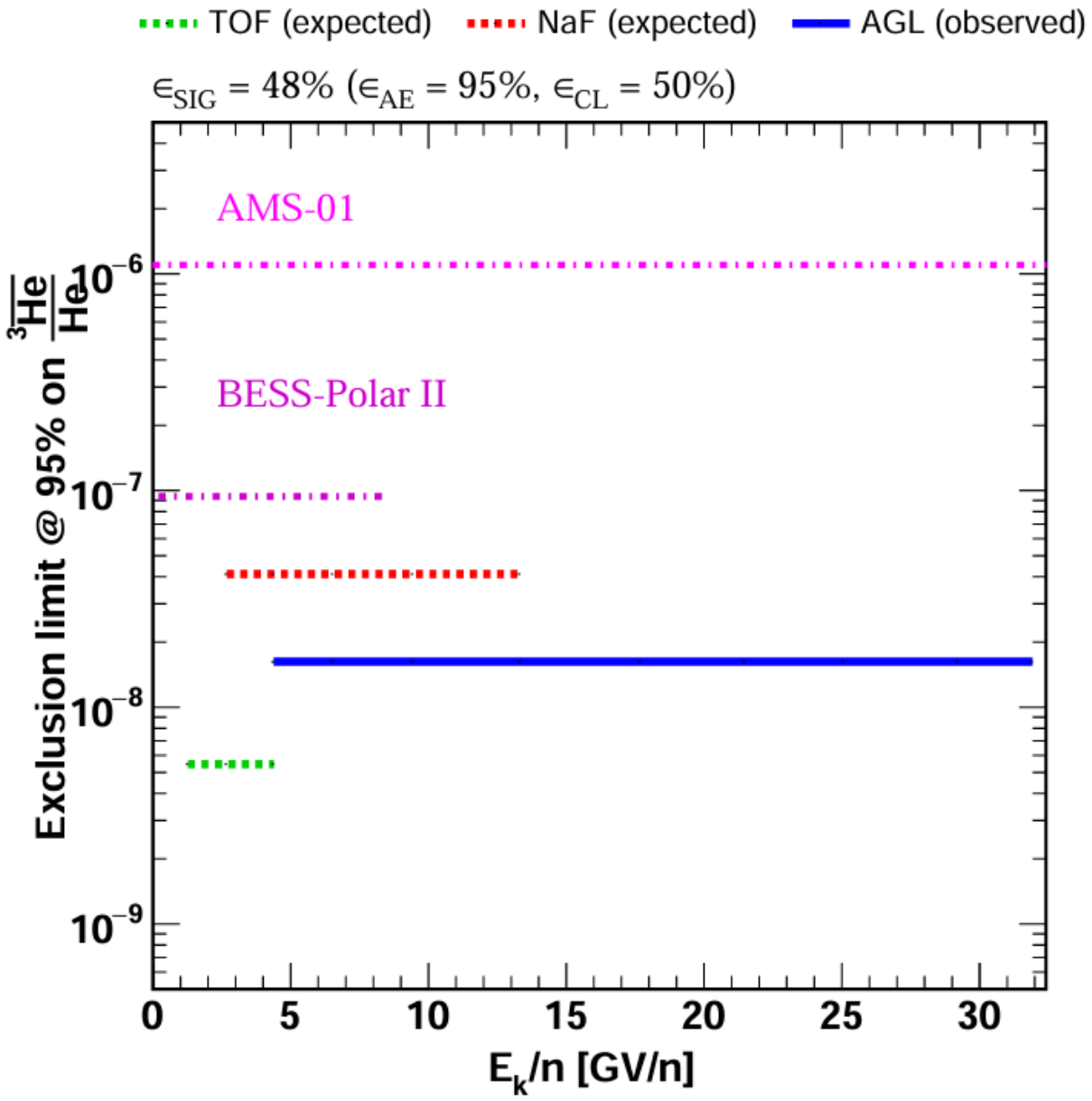
CL_b is the test of the signal significance

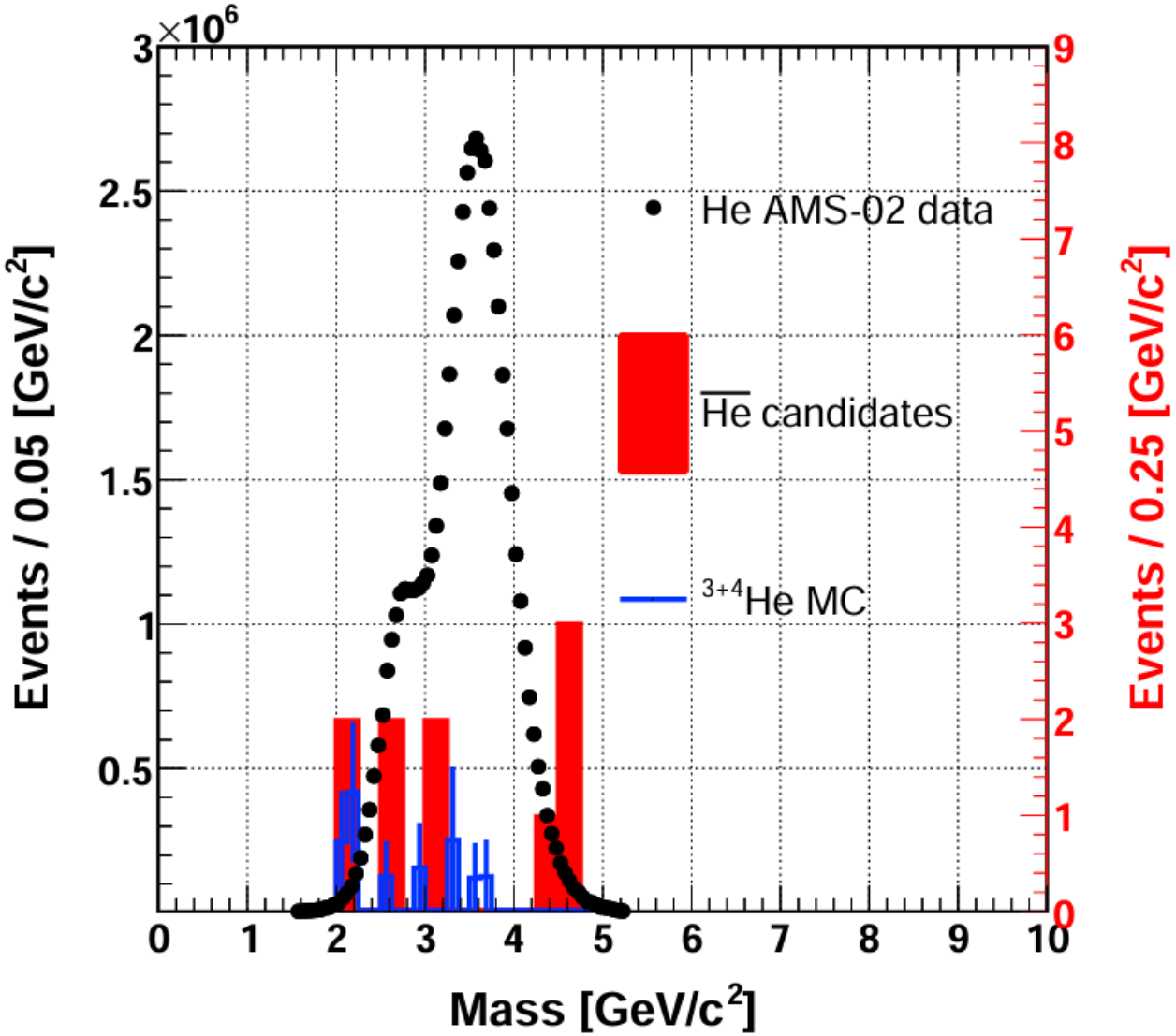


If $CL_s < 0.05$ the S+B hypothesis is rejected, identifying an exclusion limit.


Observed
Expected for background
Expected for background ± 2 σ
Expected for background ± 1 σ
$CL_s = \frac{CL_{s+b}}{1-CL_b}$
Excluded
$\overline{He}$ signal yield


Observed
Expected for background
Expected for background ± 2 σ
Expected for background ± 1 σ
CL_b
1 σ
1.5 σ
2 σ
3 σ
$\overline{He}$ signal yield


TOF (expected)
NaF (expected)
AGL (observed)
ϵ_{SIG} = 48% (ϵ_{AE} = 95%, ϵ_{CL} = 50%)
AMS-01
BESS-Polar II
$\frac{^3\overline{He}}{He}$ Exclusion limit @ 95% on
10^{-6}
10^{-7}
10^{-8}
10^{-9}
0
5
10
15
20
25
30
E_k/n [GV/n]


$\times 10^6$
3
2.5
2
1.5
1
0.5
0
1
2
3
4
5
6
7
8
9
10
Events / 0.05 [GeV/c^2]
Events / 0.25 [GeV/c^2]
Mass [GeV/c^2]
He AMS-02 data
$\overline{He}$ candidates
$^{3+4}$He MC

Conclusions

- Two **independent and orthogonal** Neural Networks have been presented:
  1. Supervised classifier quantifies the quality of the reconstructed rigidity.
  2. Unsupervised autoencoder identifies well-reconstructed events.

- 10 anti-helium candidates have been found against 4.34 ± 1.41 predicted by MC
- A $\sim 2\sigma$ tension with the BKG only hypothesis

- **Exclusion limits on the $\frac{\overline{He}}{He}$ for TOF, NaF and AGL detector.**