Geant4 simulation study of the MIDAS dosimeter/radiation monitor

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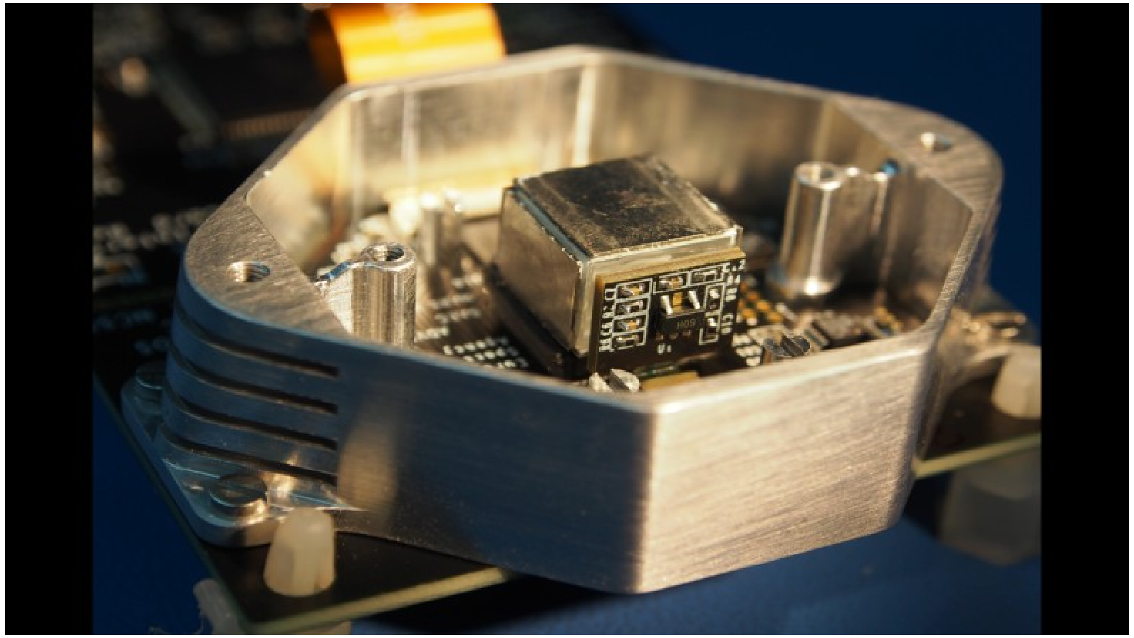
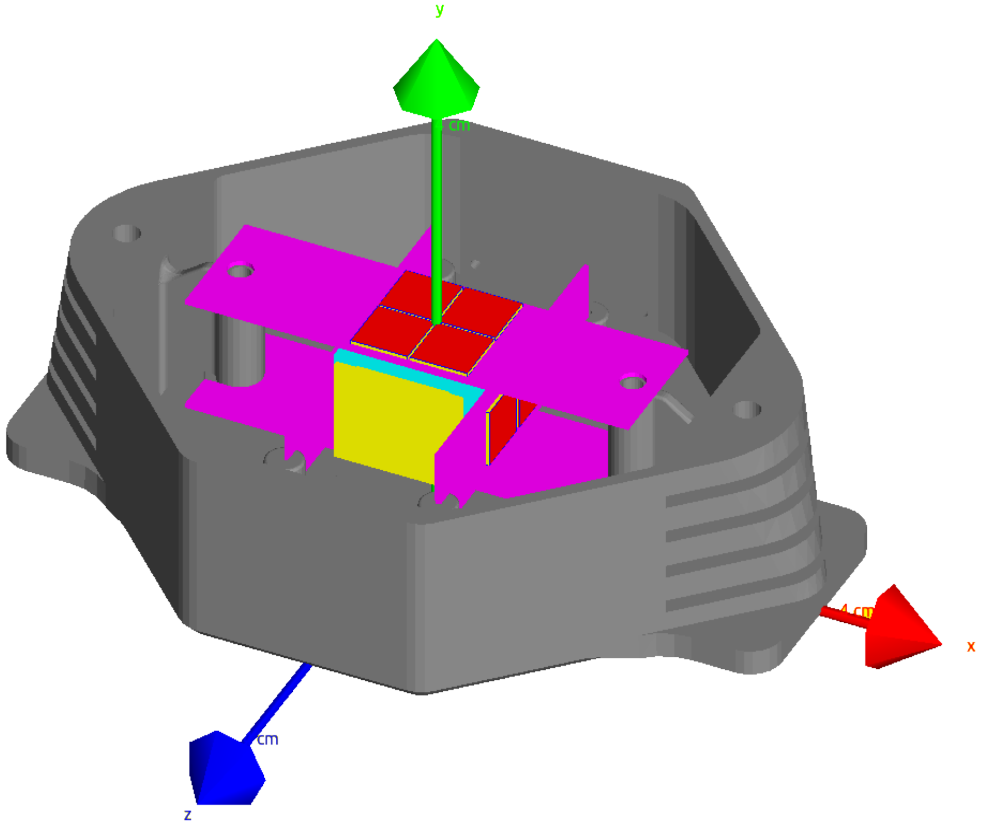
Outline

- MIDAS Detector
- Radiation Field
- Simulation Targets
- Geant4 Model
- Feature’s extraction
- Classification (particle type identification)
- Regression (kinetic energy estimation)
- Conclusions

The MIDAS device

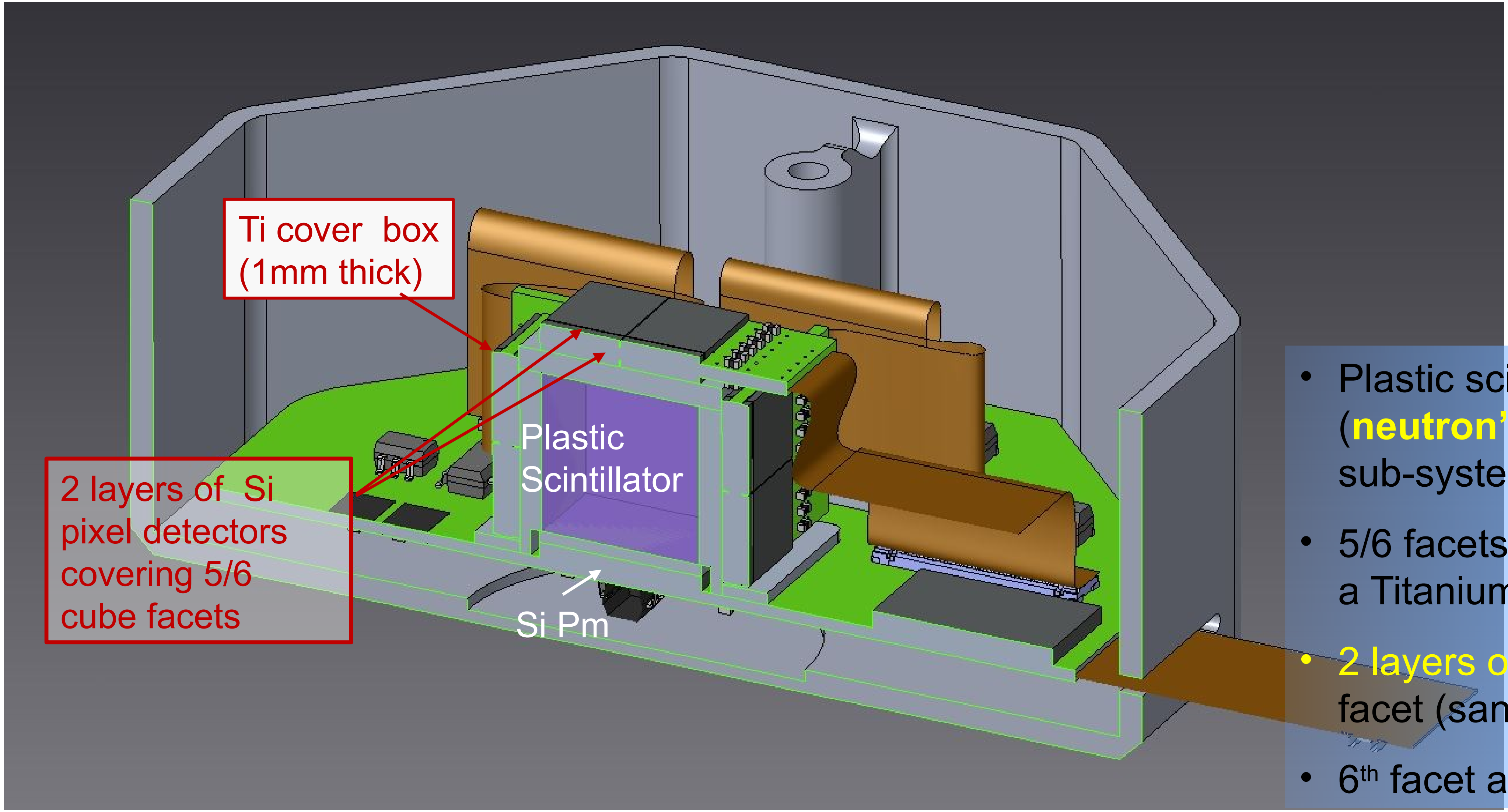
The MIDAS Device is developed in the context of a Technology Research Project funded by the European Space Agency under the contract 4000119598/17/NL/LF for a “Highly miniaturized ASIC radiation detector”

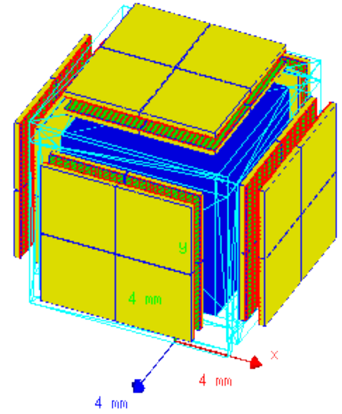




The first prototype of the MIDAS device (left) and its geometry model inserted in Geant4 toolkit (right)

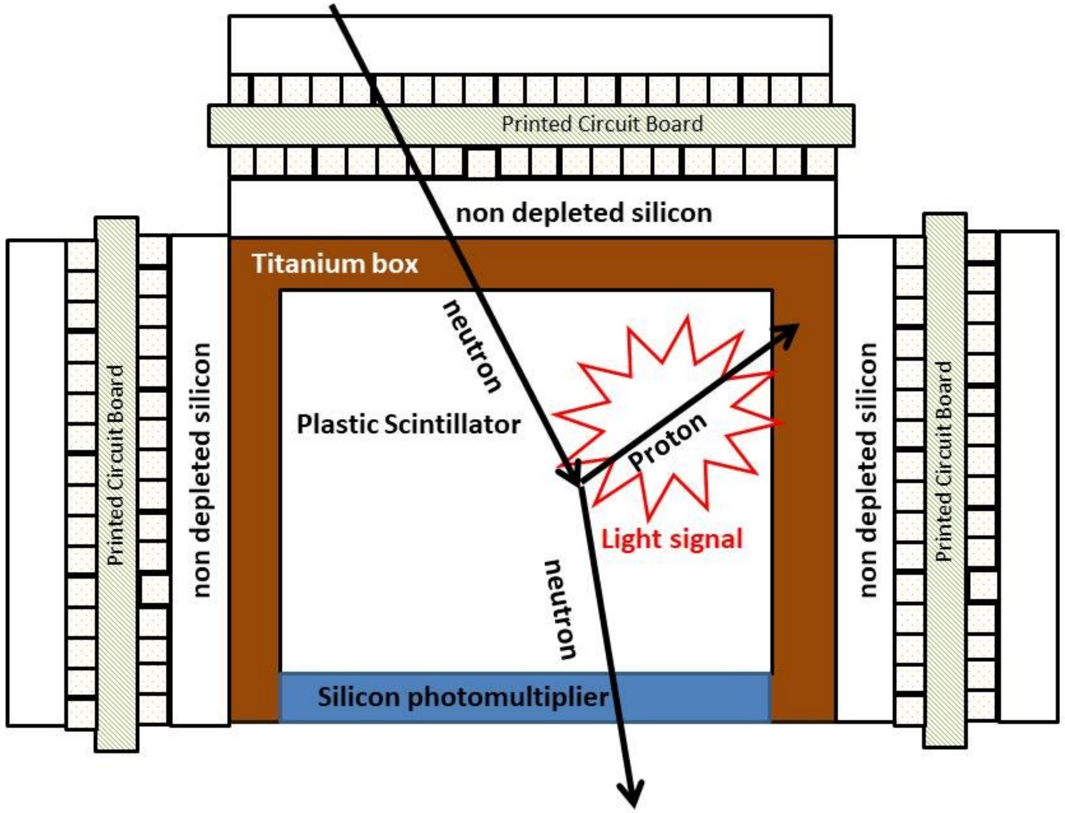
Cross-section of the detecting head

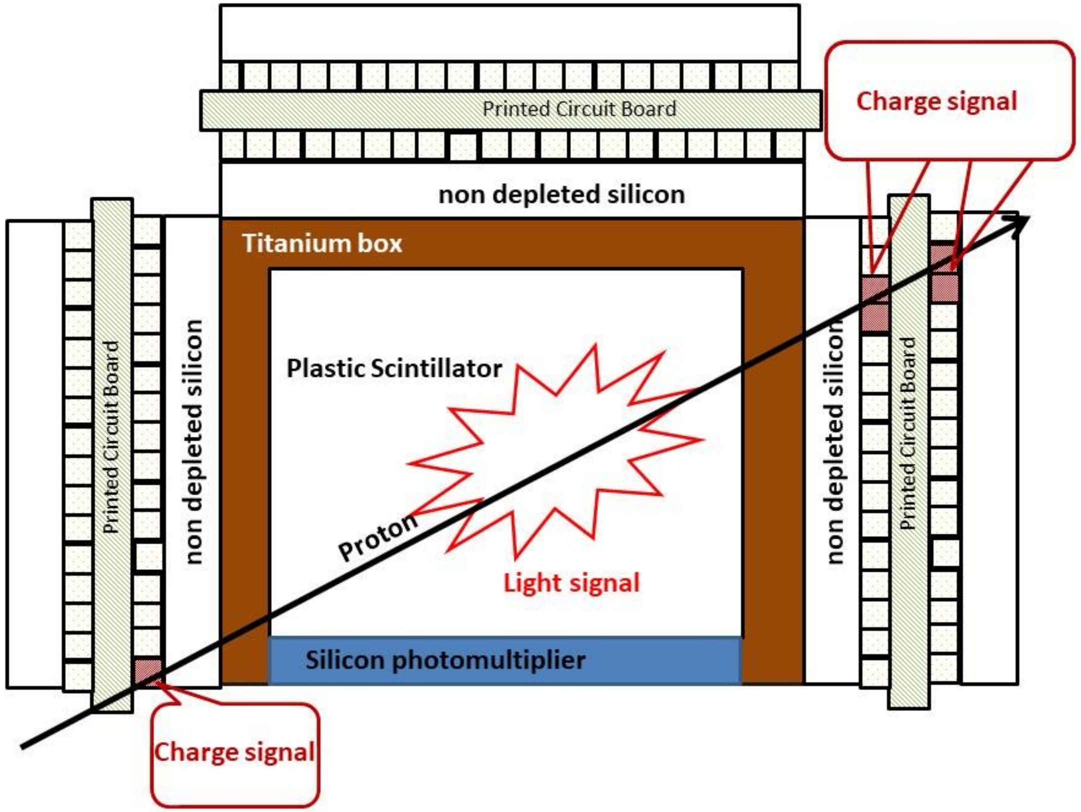




- Plastic scintillator cube (**neutron's** detecting sub-system)
- 5/6 facets are covered with a Titanium (Ti) box
- 2 layers of Si on each Ti facet (sandwiched)
- 6th facet attached to a SiPM

The device concept

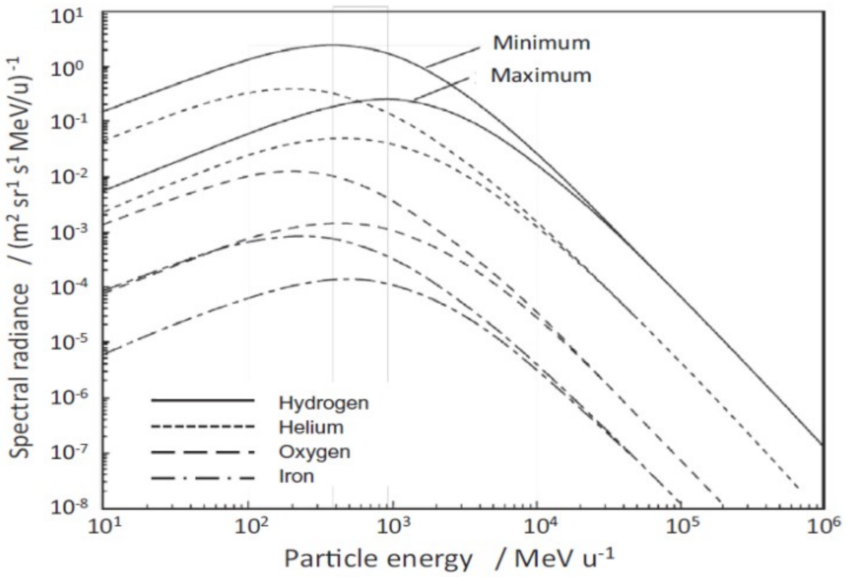




recoil particle E_{kin}<18MeV
⇒ no signal at Si layers

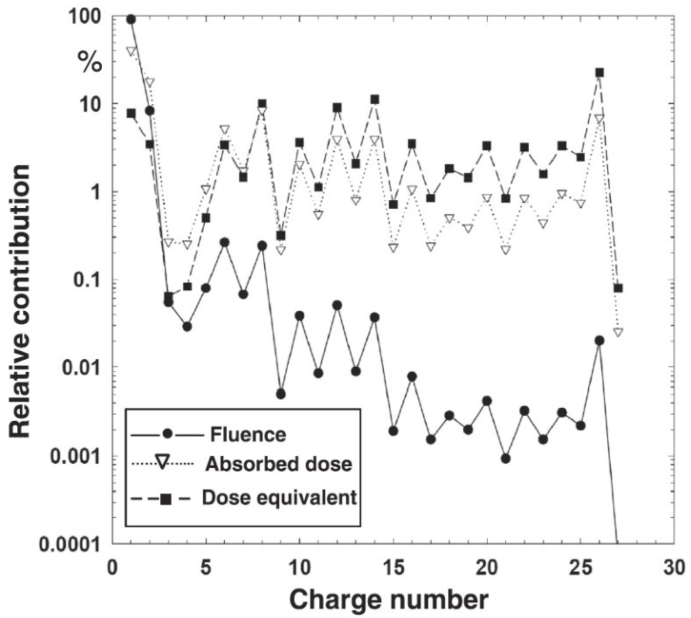
Charged particles traversing the detector
⇒ Signal at both Si layers and scintillator

Radiation fields in Space



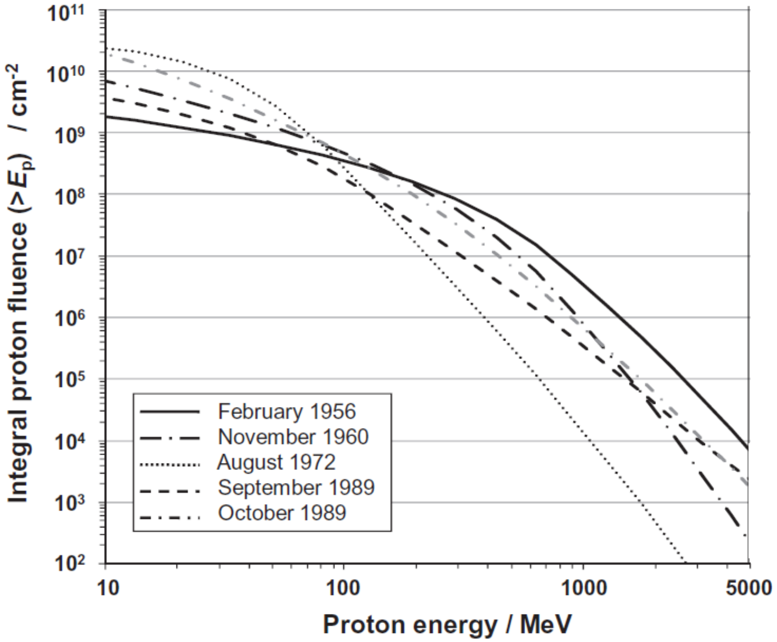
Energy distribution of radiance vs particle energy for four galactic cosmic radiation particles and their modification by solar activity [for solar minimum (1977) and solar maximum (1959)

Badhwar, G.D., The radiation environment in low earth orbit, and ICRP 123.



Elemental composition of galactic charged particles in free space and their relative contribution to absorbed dose and dose equivalent in tissue

Cucinotta et al., Space Radiation Cancer Risk Projections for Explorative Missions: Uncertainty Reduction and Mitigation, and ICRP 123



Integral fluence spectra of protons from historical ‘worst-case’ solar particle events

Kim et al., Radiation dose assessments of solar particle events with spectral representation at high energies for the improvement of radiation protection, and ICRP123

Quantities to be determined

(excerpt from ICRP[1] publication 123)

Quantities to be measured are radiation fluence rates, the energy distributions of different types of particles and linear energy transfer (LET) distributions.

One may either calculate organ doses in a body using the radiation field data outside of the spacecraft and a code that combines radiation transport into the spacecraft and into the human body,

Or

one may assess the radiation field parameters near to an astronaut and then apply fluence to dose conversion coefficients for all types of particles involved for the assessment of organ doses

(1) International Commission on Radiological Protection

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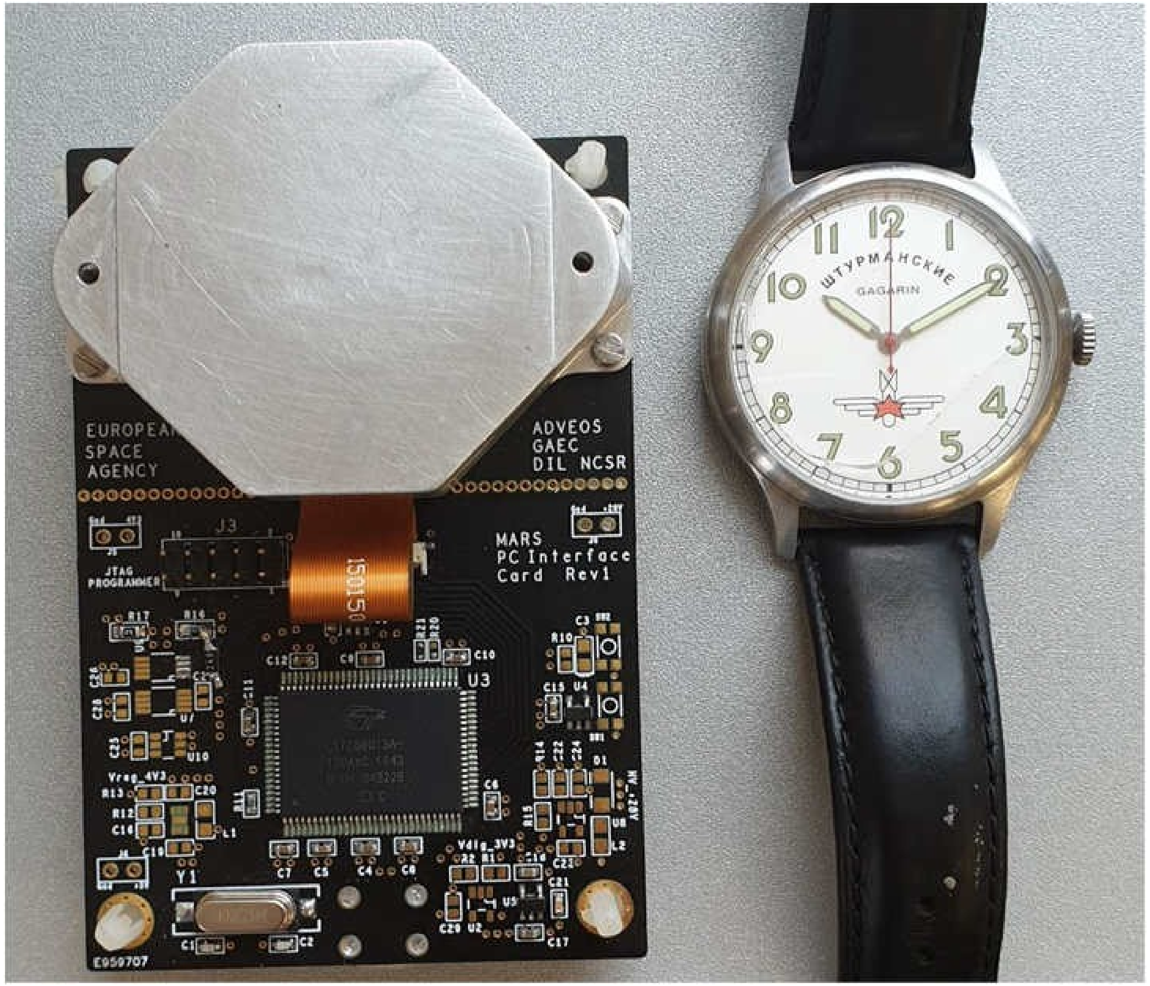


(1) International Commission on Radiological Protection

MC Study Targets (until now)

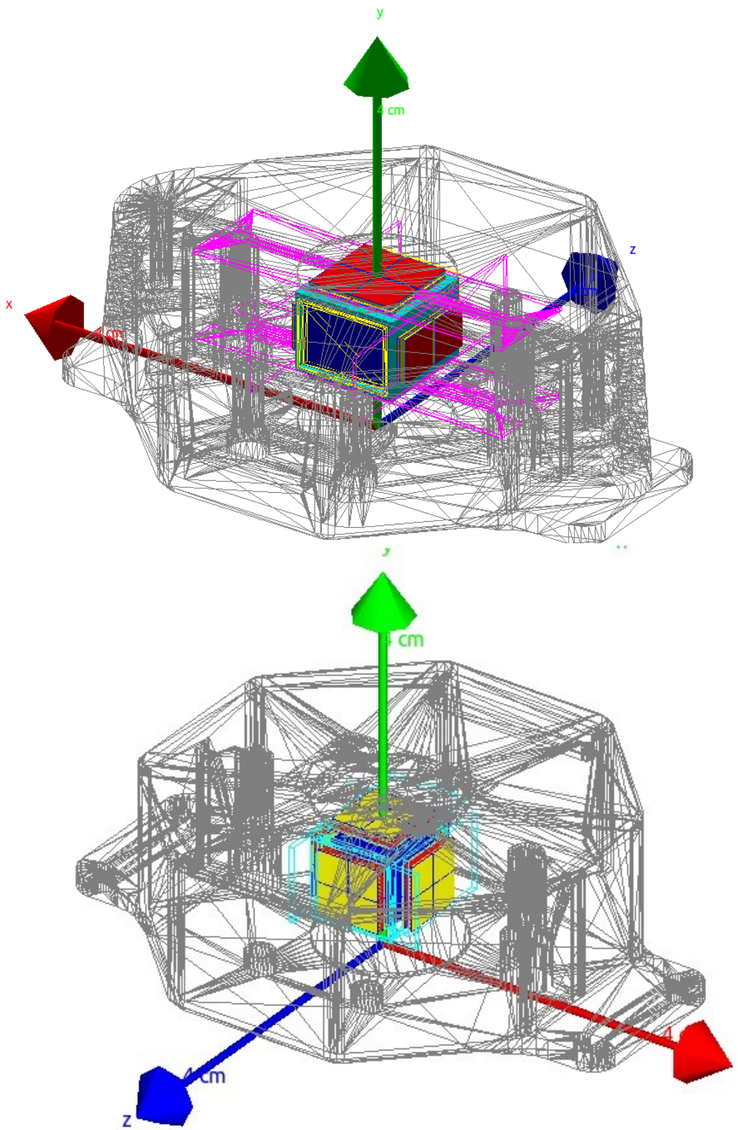
Investigate the possibility to determine:

- The **type** of the **charged** particles that traverse the detector
- The **energy** of the **charged** particles that traverse the detector
- The **neutron** fluence spectra

Using the per event information recorded by the detector :

- Deposited Energy
- Topological structure of the deposited energy

Geant4 models



Geometry models for the 1st and 2nd version of the device

<u>Physics lists:</u>
High Precision (HP) Models
QGSP_BERT_HP

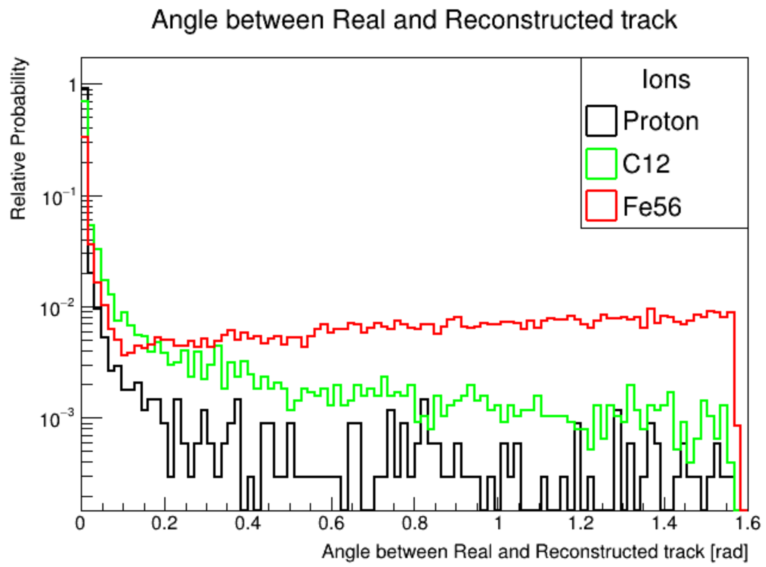
<u>Sources</u> (particle guns, isotropic spherical sources)

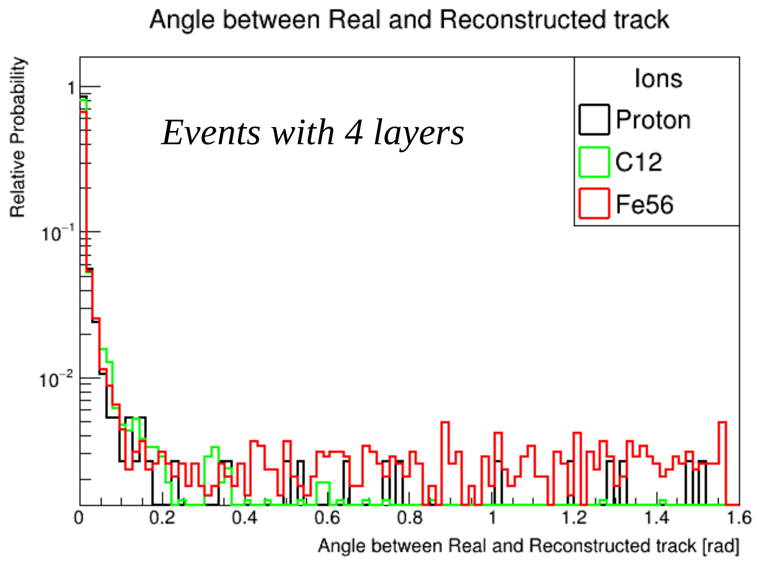
- Particle beams for protons, iron, neutrons
- Isotropic sources both mono-energetic and with GCR spectral densities for the following particles:

  Protons, ^{4}He, ^{12}C, ^{14}N, ^{16}O, ^{20}Ne, ^{28}Si, ^{40}Ca, ^{48}Ti and ^{56}Fe ions.
- Sources based on the GCR spectrum are provided by OMERE

Pre-processing: track finding

- Energy deposition is registered in Si pixels (105.5×105.5×50 μm^3).
- Clusters of hits are defined using the barycenter of energy depositions (hits) above 20keV in each Si layer.
- The charged particle track is estimated as a 3D line fitted to the barycenters of the most energetic clusters.
  - If the sum of square distance of the line from the cluster centers is less than 0.001 mm^2, the directional cosine with respect to the vertical direction of incidence is calculated.
- Only events with 4 layers participating in the 3D line fit are used (reduced sample)

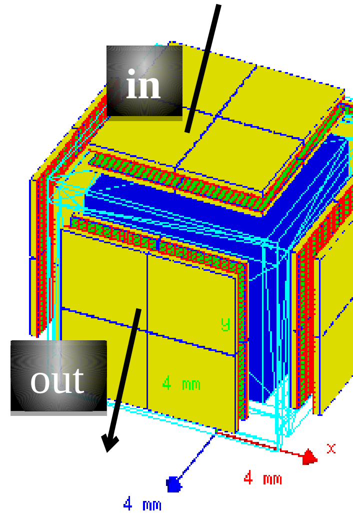




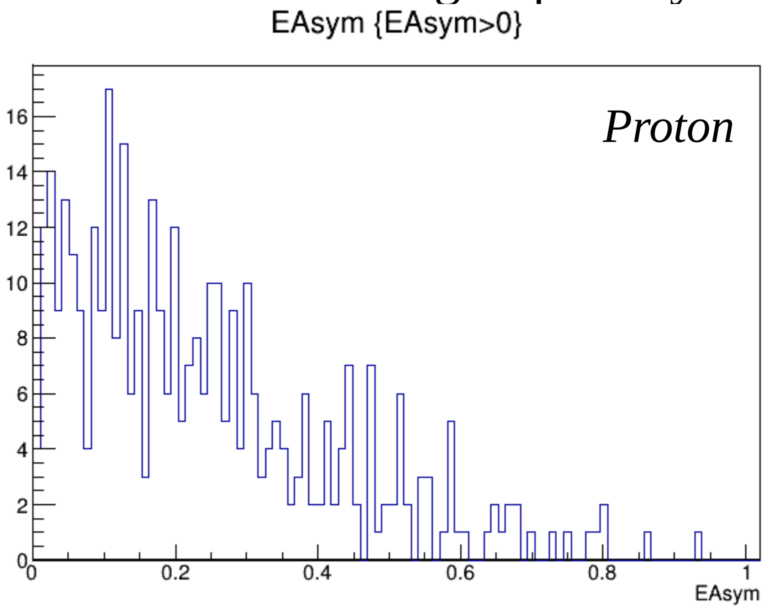
Pre-processing: E_{asym}

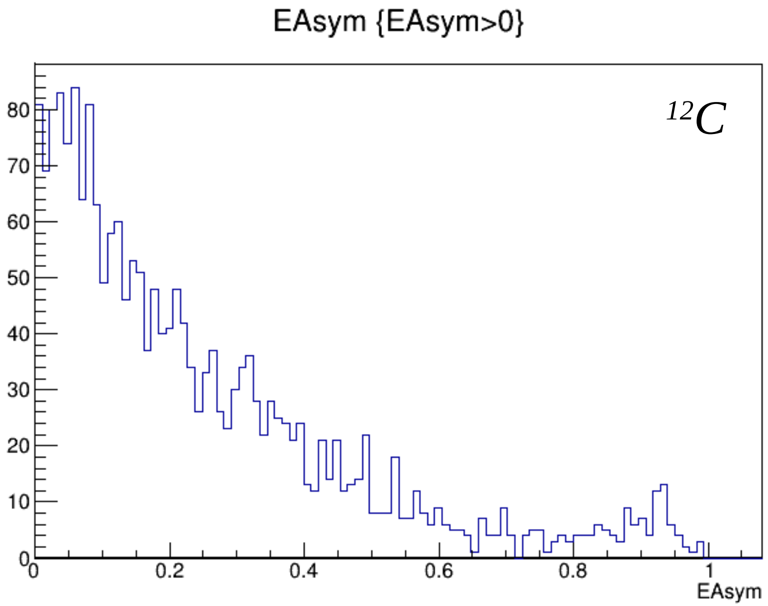
- The absolute value of the deposited energy asymmetry, E_{asym}, between inbound (E_1, E_2) and outbound (E_3, E_4) groups of consecutive Si layers is calculated as

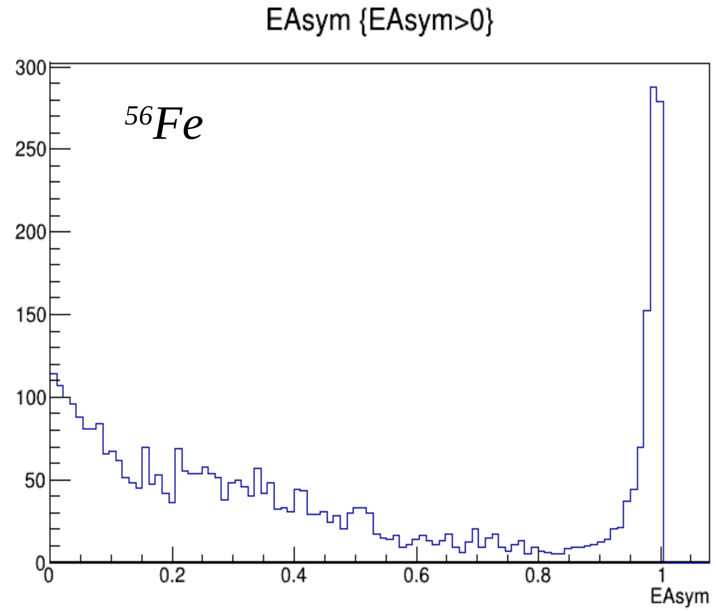
$$E_{asym} = \left| \frac{(E_1 + E_2) - (E_3 + E_4)}{E_1 + E_2 + E_3 + E_4} \right|$$



- Events with $0 < E_{asym} < 0.9$ are selected to avoid misleading δ-rays traversing the outbound group of layers

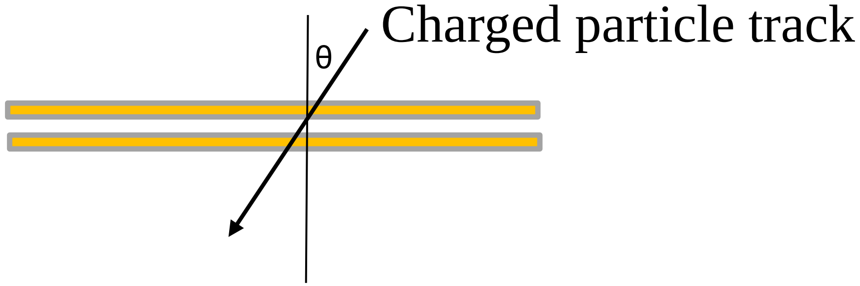


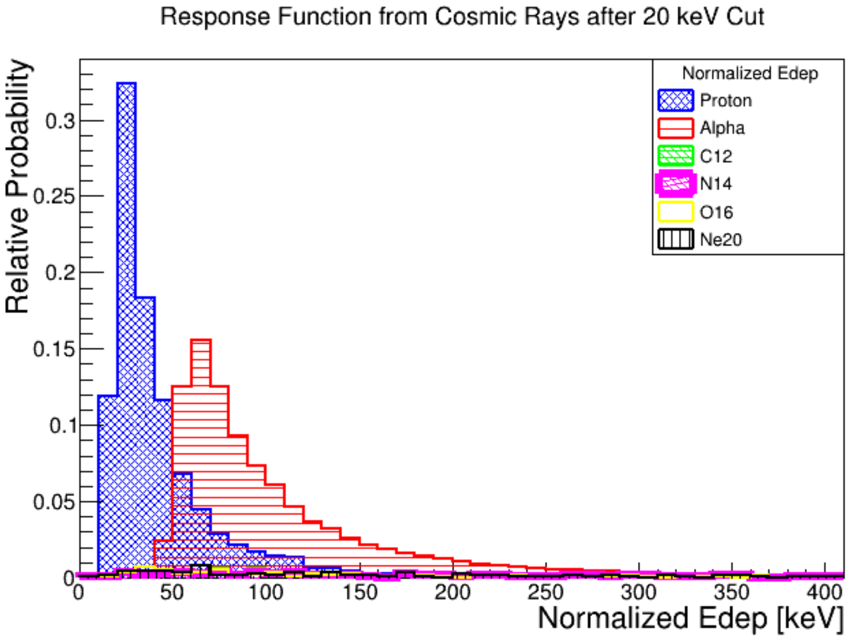


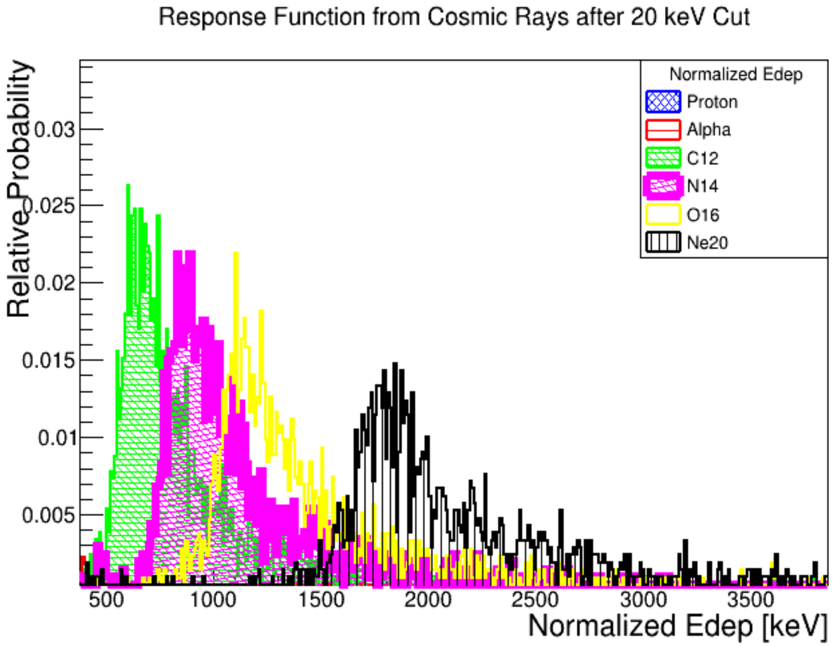


Features extraction

(1) $\text{Normalized } E_{dep} = E_{dep} \times \cos\theta$

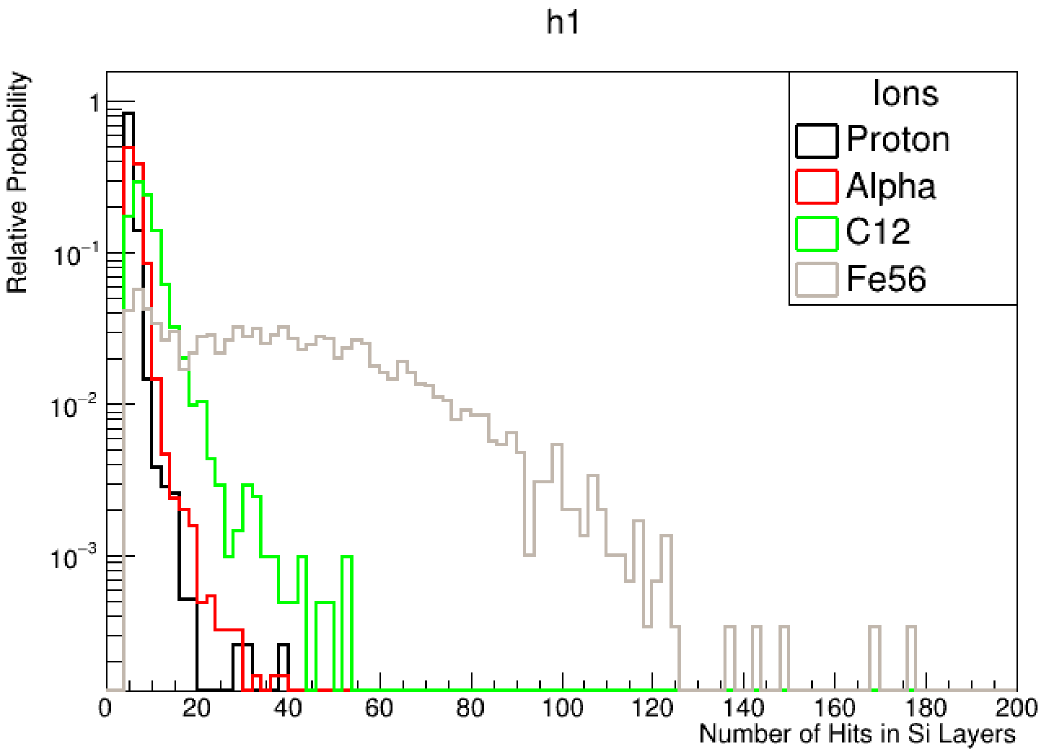




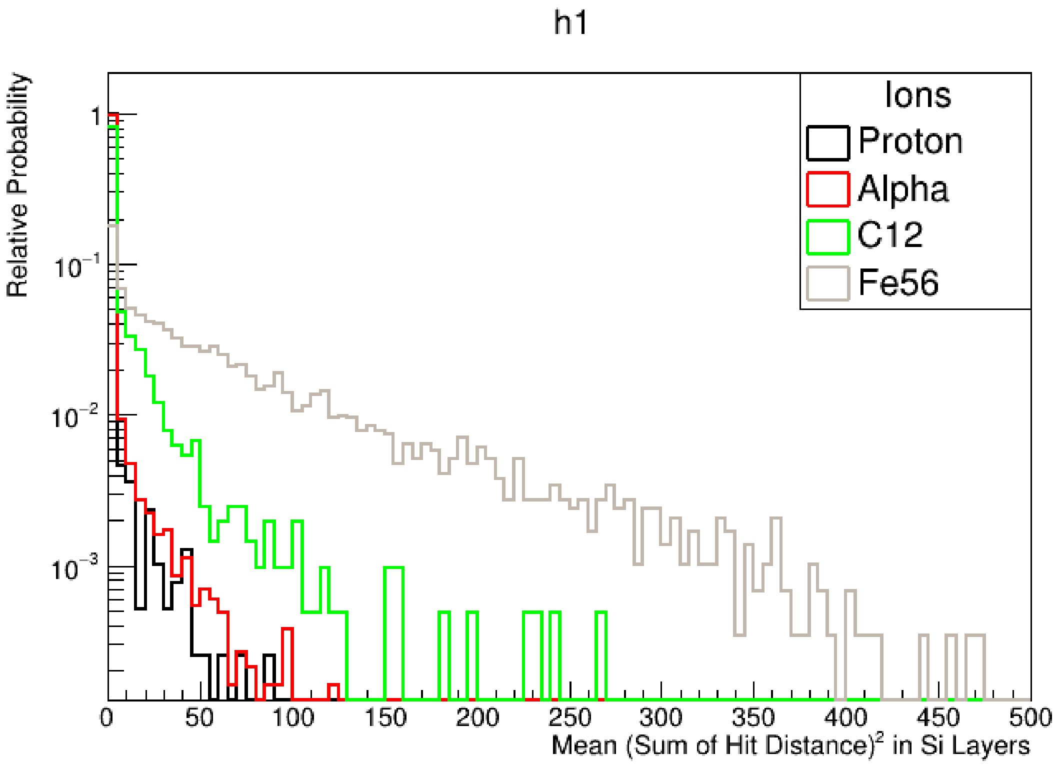


Features: (cont'd)

(2) Number of pixel hits per event

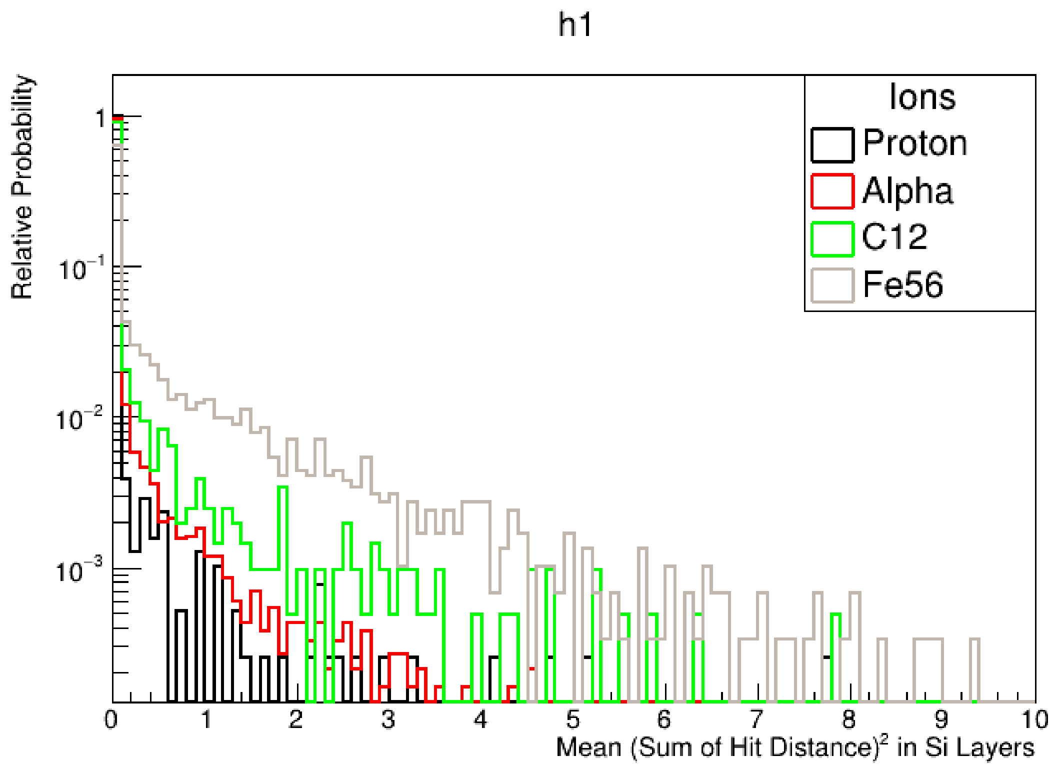


(3) The sum of squares distance of the pixel hits from the cluster barycenter.
The mean sum of squares in the 4 track layers is used

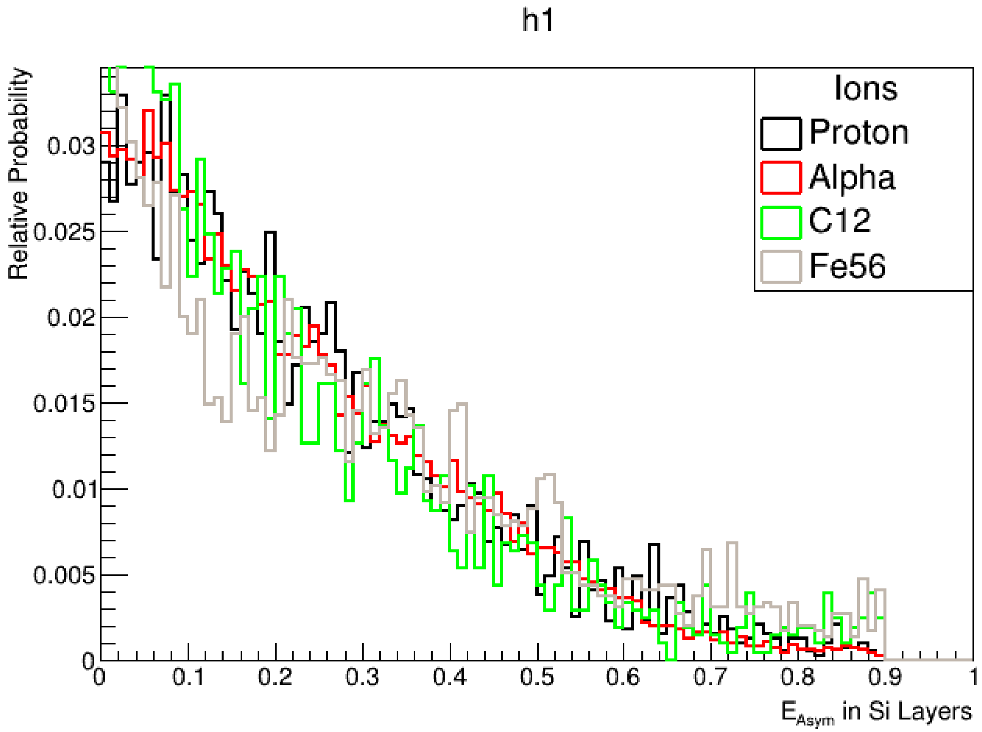


Features: (cont'd)

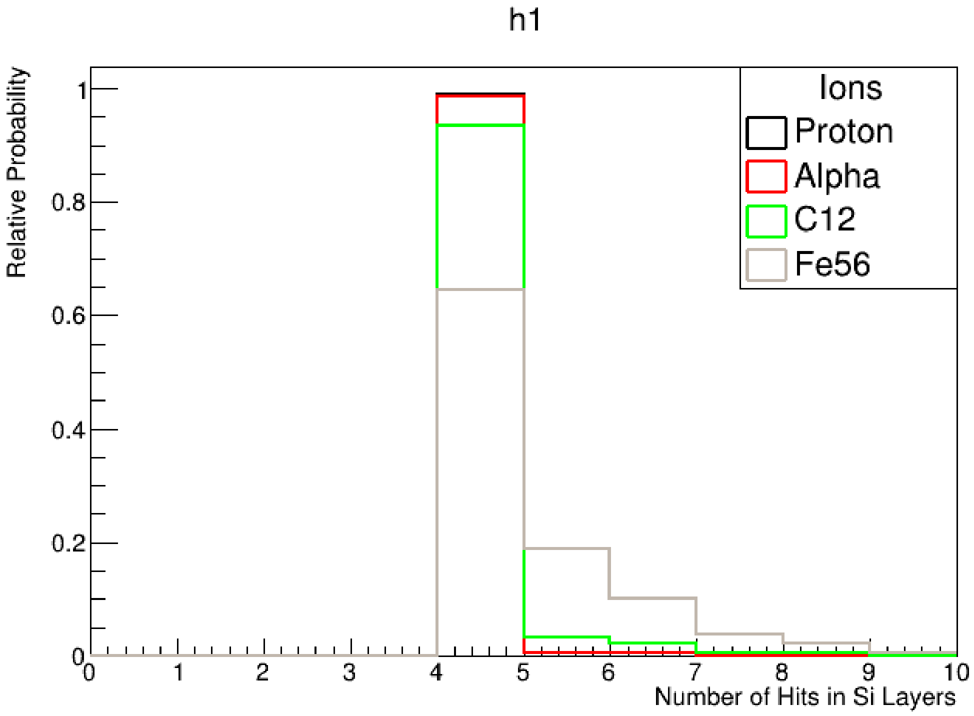
(4) The mean weighted sum distance of the pixel hits from the cluster barycenter with weight $E_{Hit}/E_{cluster}$



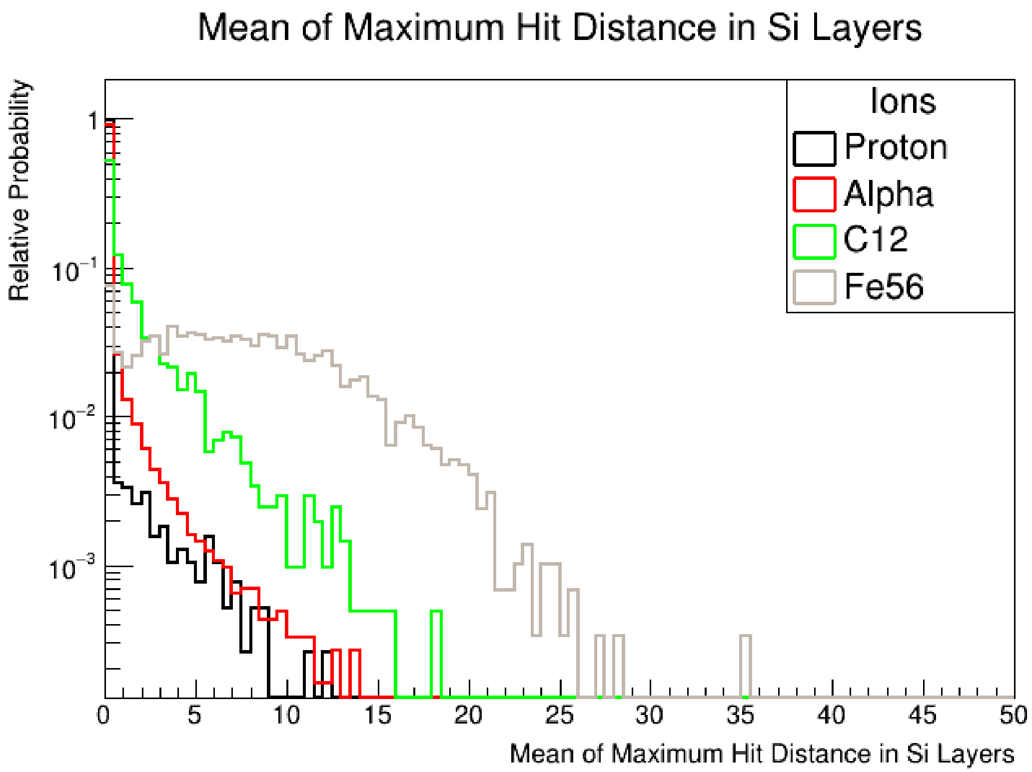
(5) The *absolute* value of the energy asymmetry, E_{asym}, between "in" and "out" layers (based on the track reconstruction) with $0 < E_{asym} < 0.9$



(6) The number of hits in active layers i.e. layers with recorded energy above 20keV

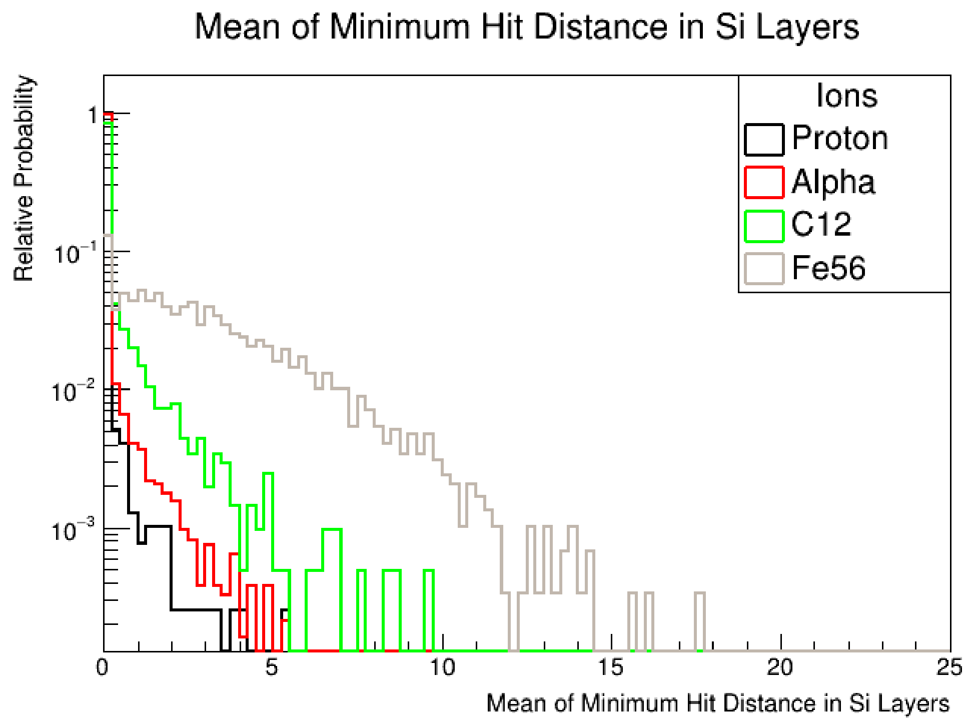


(7) The mean (in the 4 Si layers) of the **maximum** distance of a hit from the cluster’s barycenter.

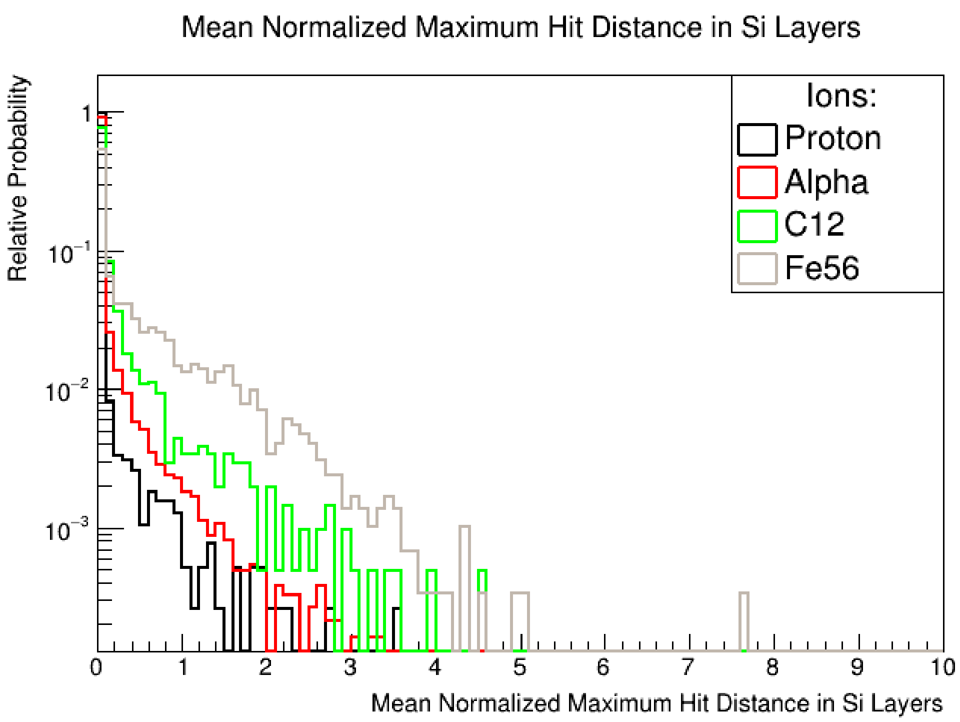


Features: (cont'd)

(8) The mean (in the 4 Si layers) of **minimum** distance of a hit from the cluster's barycenter

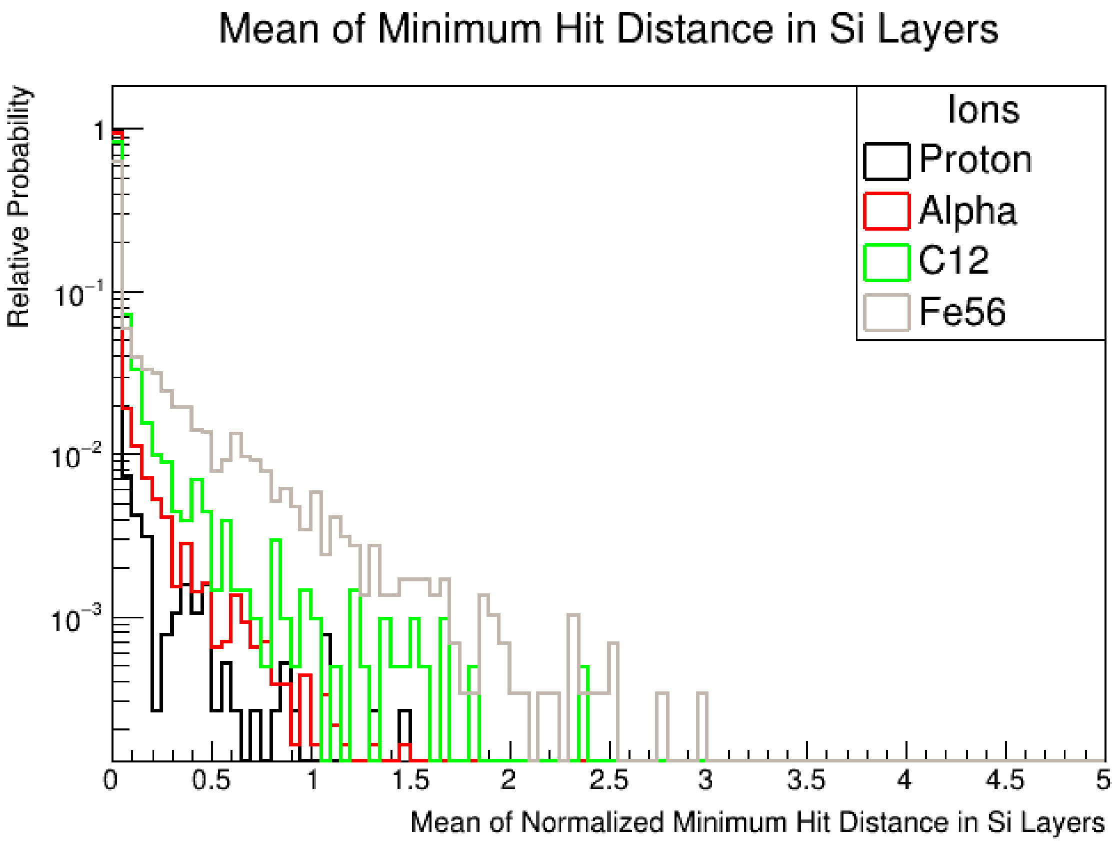


(9) The mean (in the 4 Si layers) of the weighted **maximum** of distance of a hit from the cluster's barycenter with weight $E_{Hit}/E_{cluster}$



Features: (cont'd)

(10) The mean (in the 4 Si layers) of the weighted **minimum** of distance of a hit from the cluster's barycenter with weight $E_{Hit}/E_{cluster}$



Classification methods

The problem of finding the type of the impinging particle is handled as a multi-classification problem between:

- Protons, ^{4}He, ^{12}C, ^{14}N, ^{16}O, ^{20}Ne, ^{28}Si, ^{40}Ca, ^{48}Ti and ^{56}Fe

The problem of finding the kinetic energy of a primary particle is handled as a regression problem. (applied to protons only until now)

The Toolkit for Multi-Variate Analysis (TMVA) package[1] has been used

We've tested
- Gradient Boosted Decision Trees (BDTG)
- Deep Neural Networks (DNN_CPU)
- Multi-Layer Perceptron (MLP)

but the best performance is achieved by BDTG and DNN

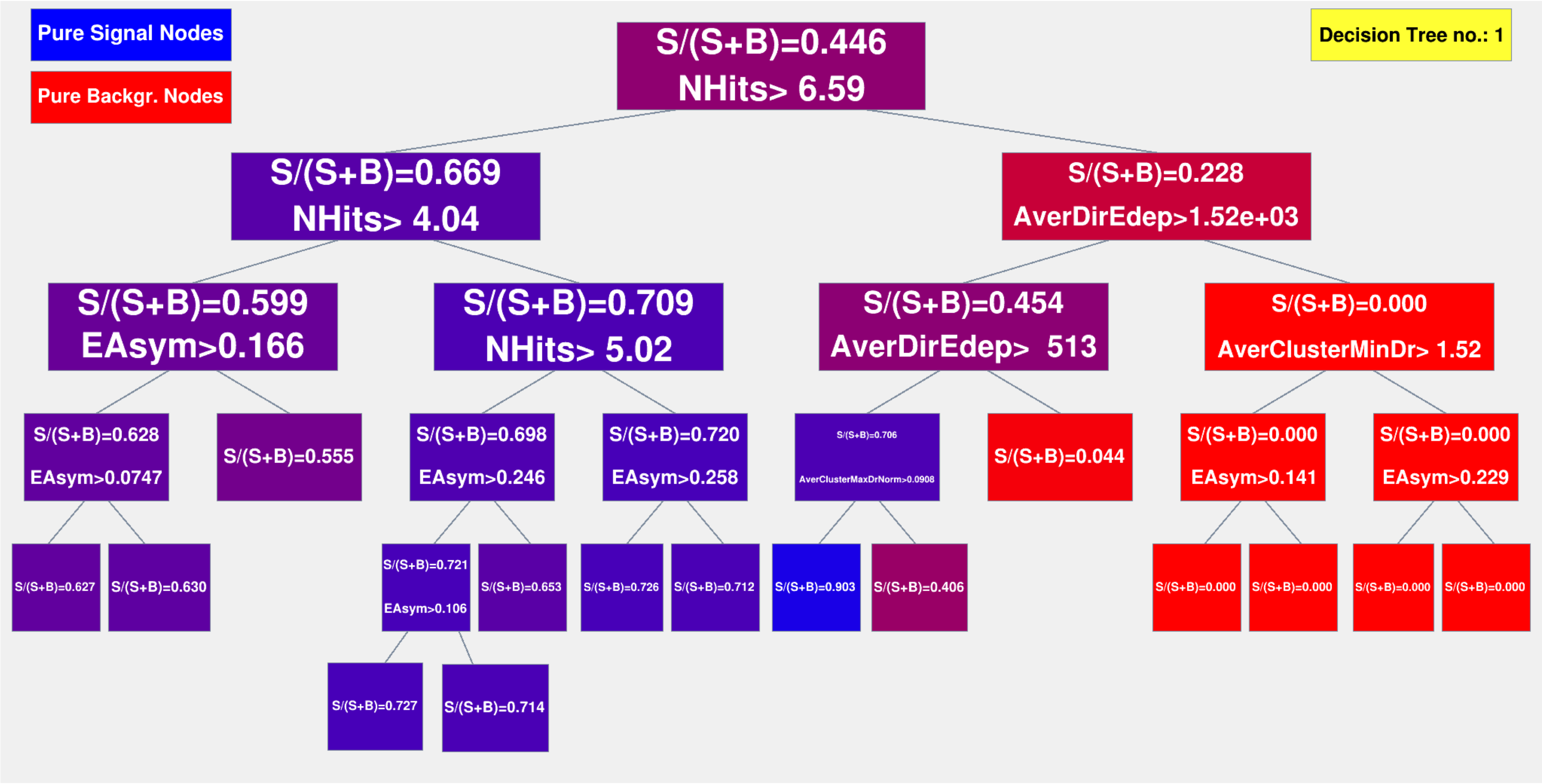
[1] A. Hoecker, P. Speckmayer, J. Stelzer, J. Therhaag, E. von Toerne, and H. Voss, TMVA - Toolkit for Multivariate Data Analysis, PoS ACAT 040 (2007), arXiv:physics/0703039

Gradient Boosted Decision Trees (BDTG)

DT in general consists of a

- Consecutive set of questions (nodes)
- Yes/No decision
- Final verdict (leaf) is reached after a given maximum number of nodes

(*Trained phase is required*)

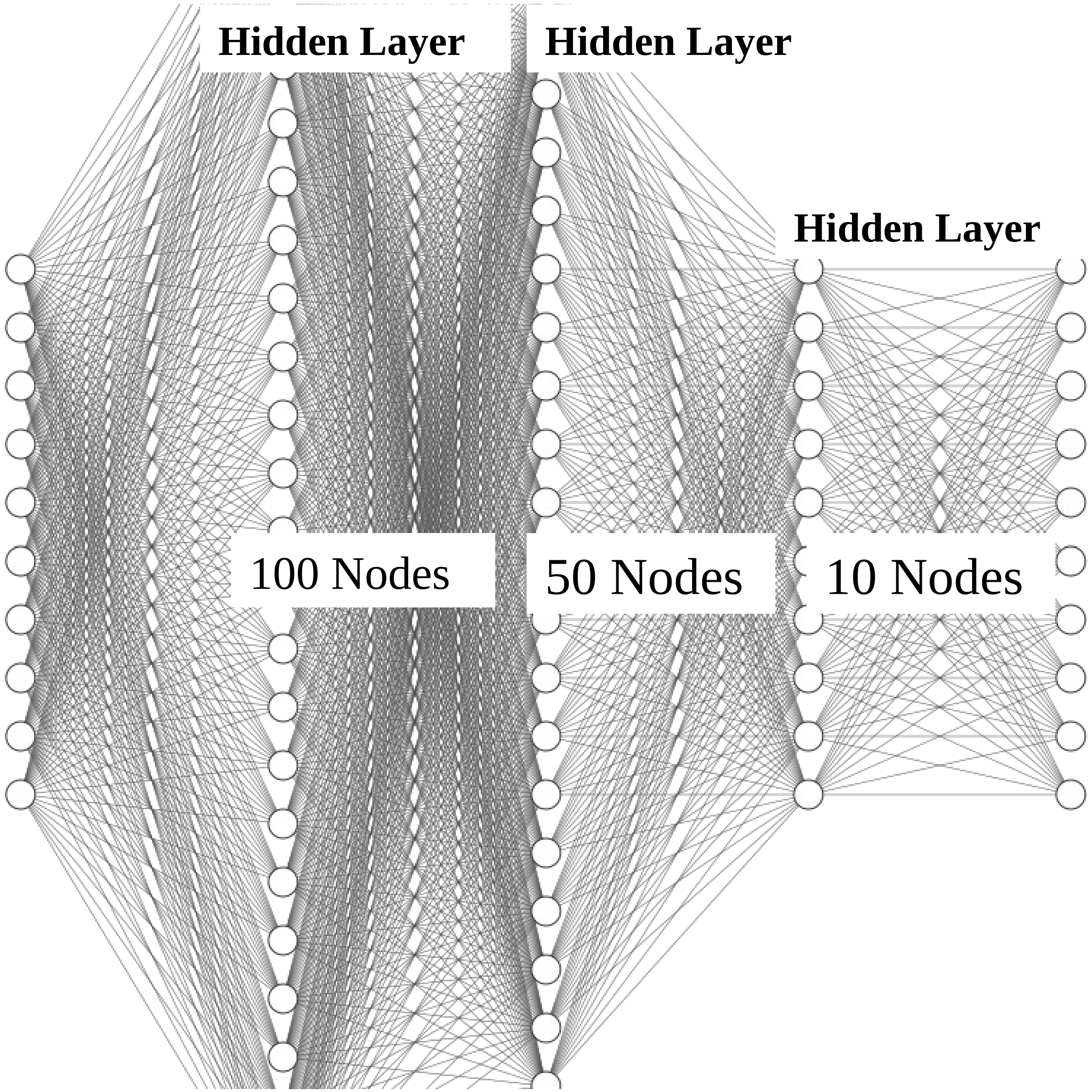


DTs suffer from instabilities

- Create a forest of trees
- Each misclassified event is reweighted (boosted)
- A scoring algorithm that spans through all trees defines the final decision

Deep Neural Networks (DNN)

Event Features
as inputs

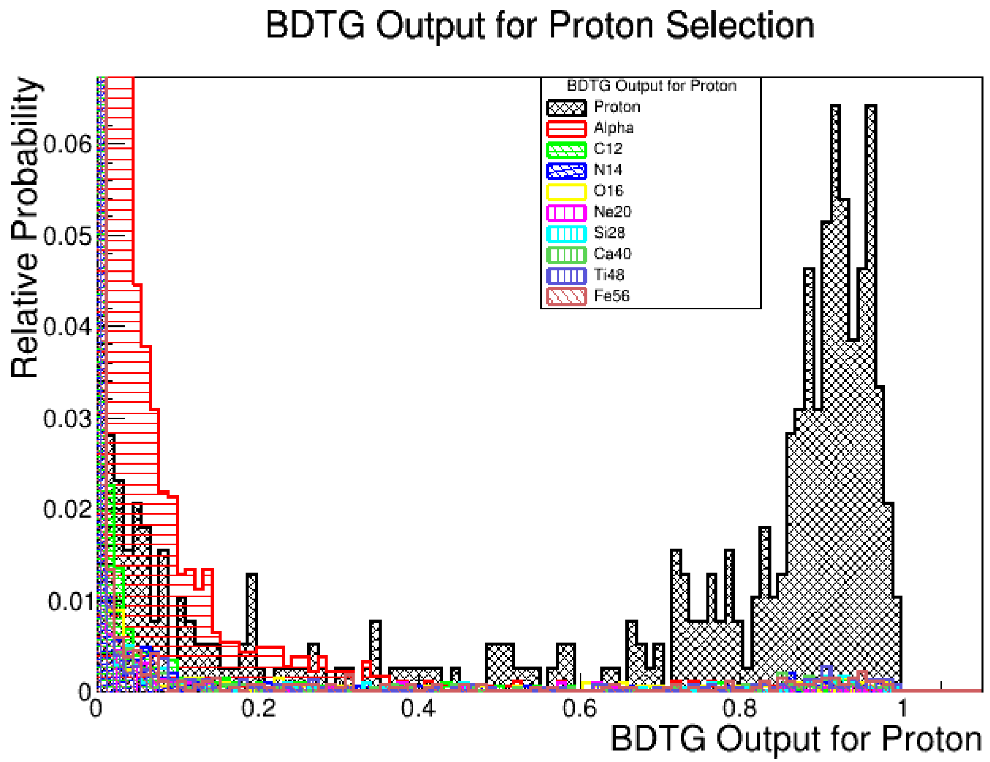


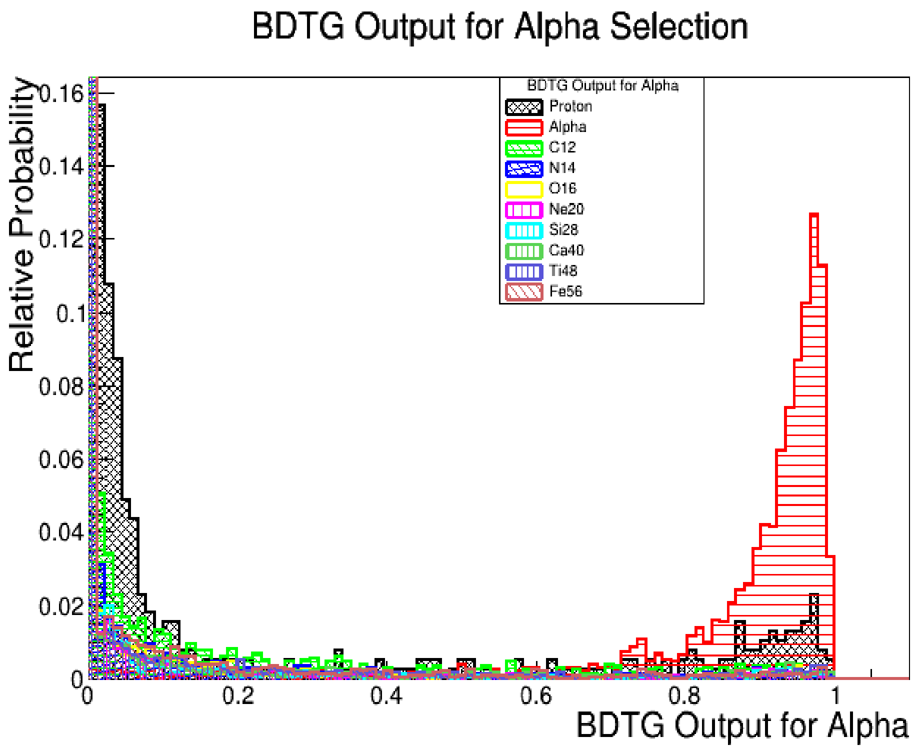
One output for
each particle type

Particle classification: BDTG$_{(I)}$

Gradient boosted decision trees outputs

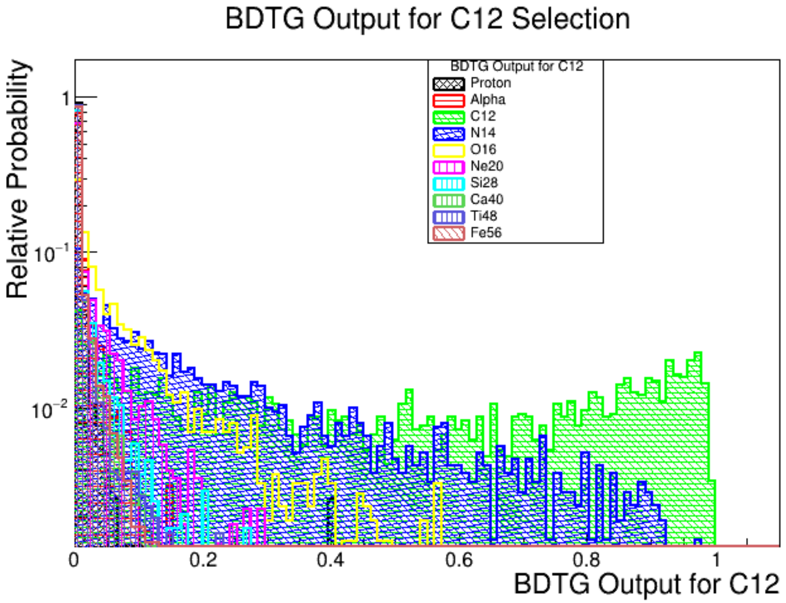
- BDTG discriminates efficiently protons (left) and alpha (right) from other particles

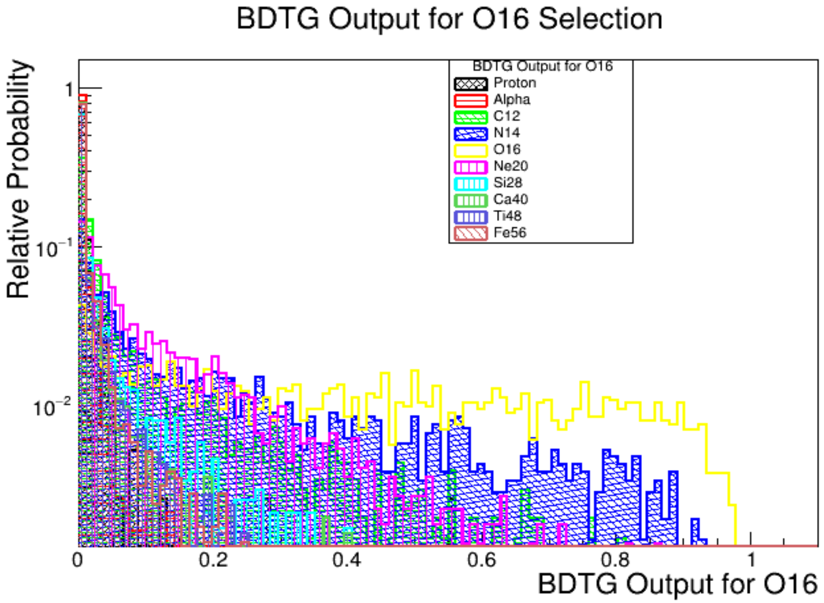




Particle classification: BDTG$_{(II)}$

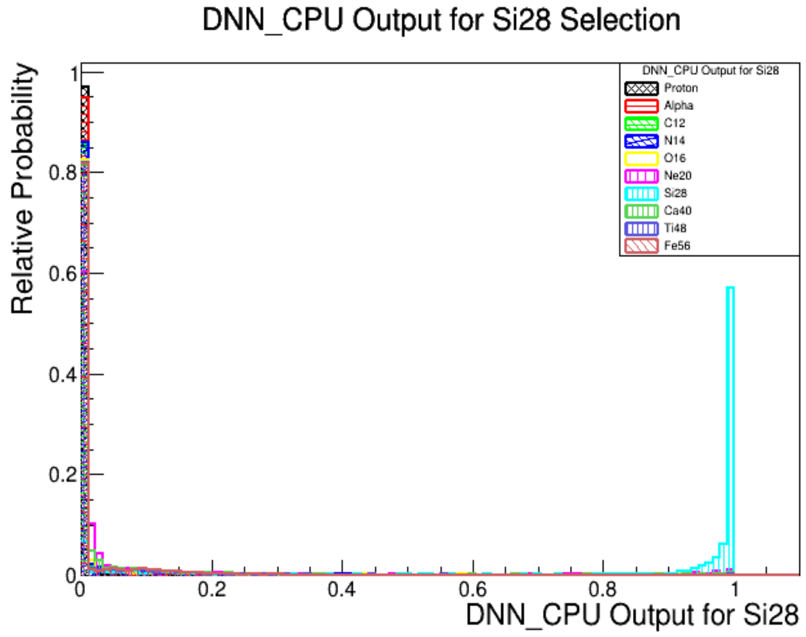
BUT, discrimination between ^{12}C, ^{14}N and ^{16}O is not sufficient

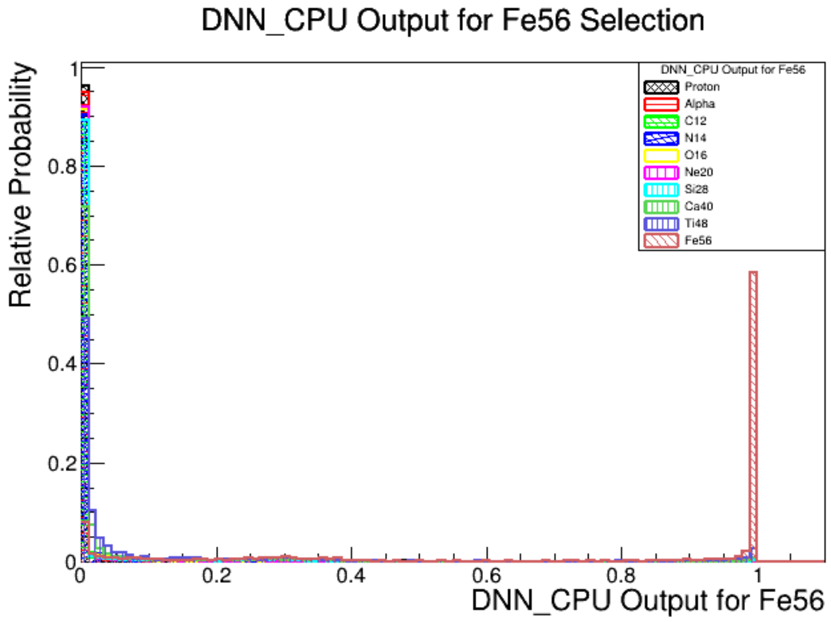




Particle classification: DNN

Classification of heavier ions is better using the Deep Neural Network Classifier.

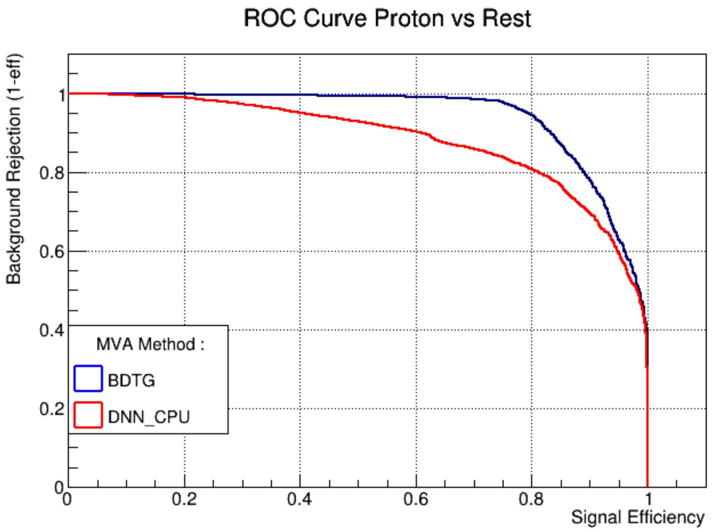


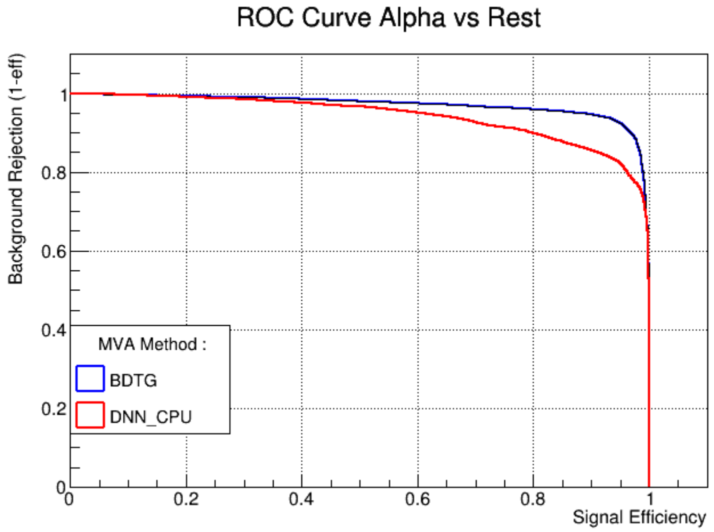


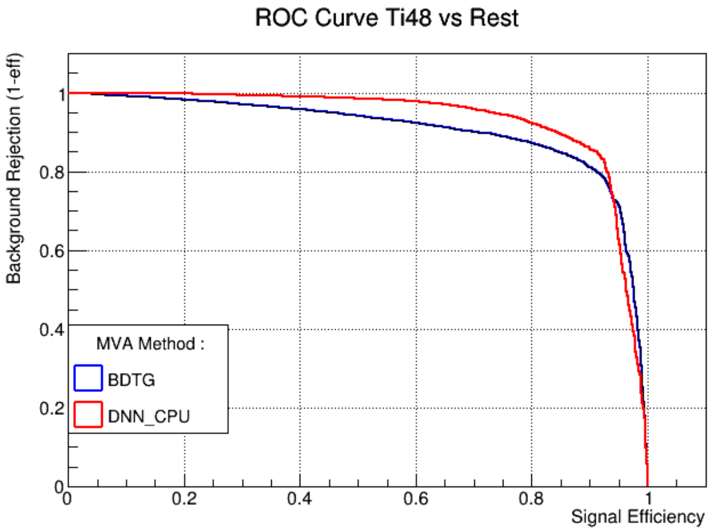
ROC Curves

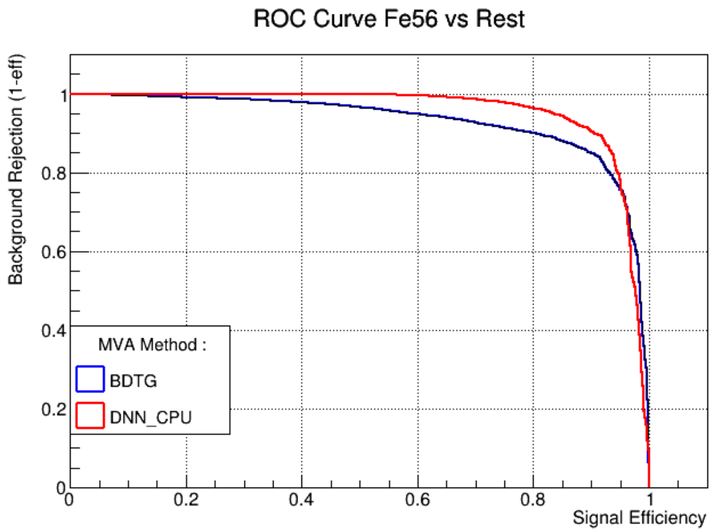
The Receiver Operating Characteristics (ROC) curves demonstrate the effectiveness of distinguishing the signal from the background

- Light particles
  BDTG (**blue** curve)
- Heavy particles
  DNN (**red** curve)









Kinetic energy estimation

The problem of finding the kinetic energy of an impinging particle is handled as a multivariate regression problem for each particle type. The method has been tested on a isotropic monoenergetic proton sample.

We've tested

- BDTG
- DNN
- Multi-Layer Perceptron (MLP)

but best performance is achieved by BDTG and MLP.

The same data sample was used as in multiclassification of ions with the same extracted features (variables) as input

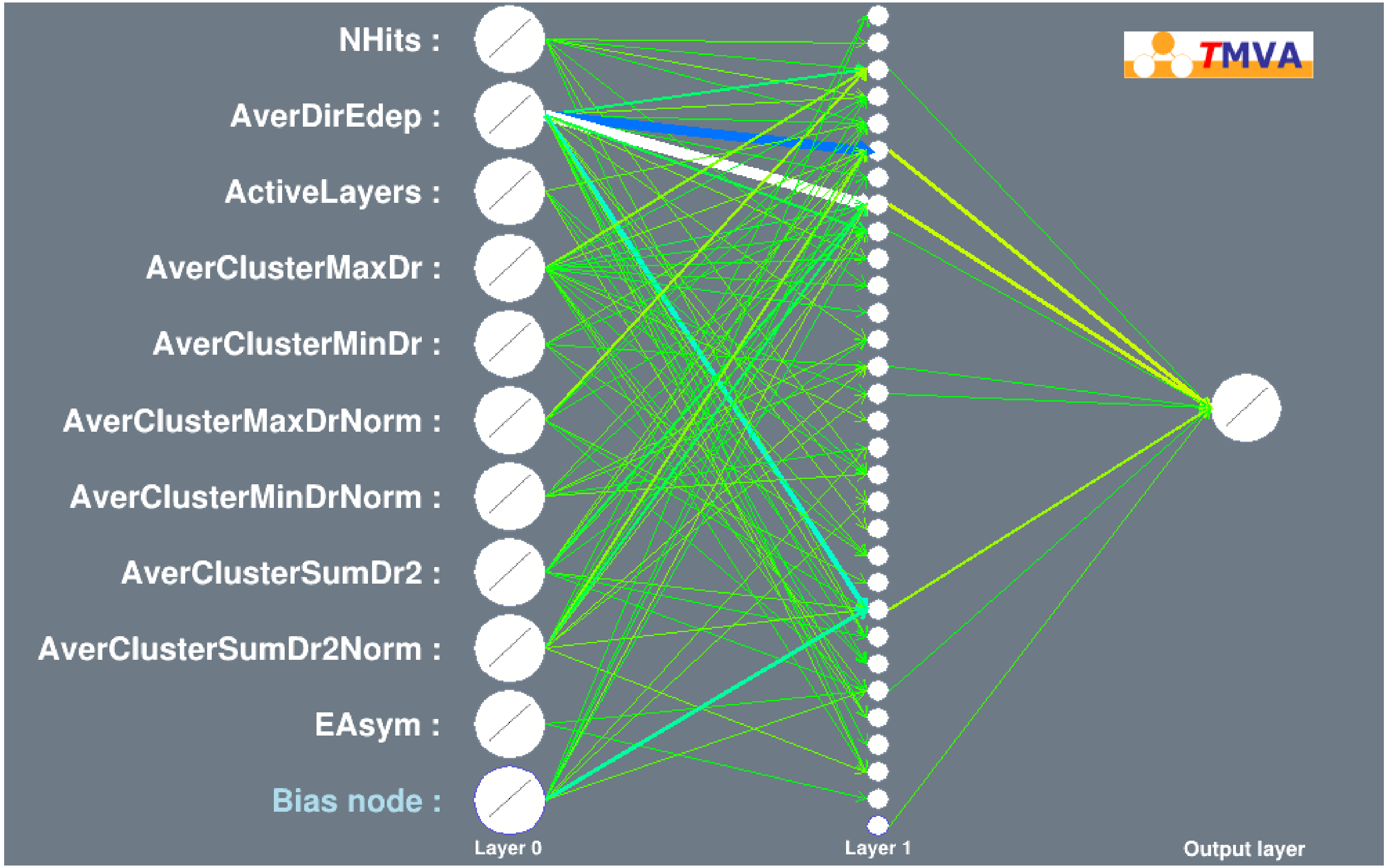
Multi-Layer Perceptron (MLP)

- Features X={x_1, x_2, …}
- Target Y={y_1, y_2, …}

the MLP can learn the relationship between the features X and the target Y based on a set of weights adjusted during the training phase via the back propagation algorithm

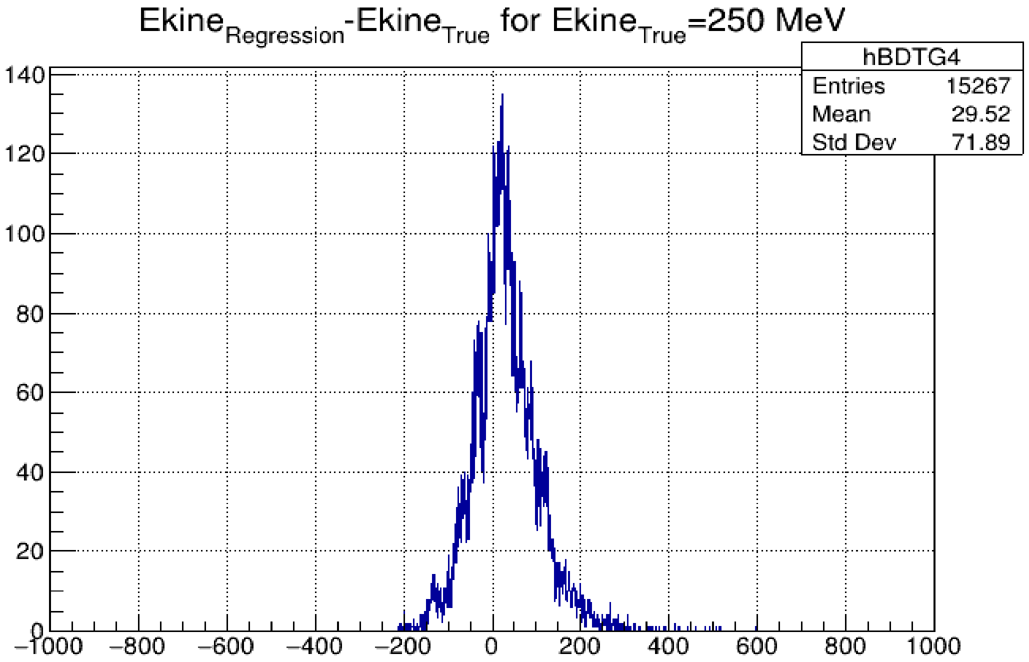
For the case of E_{kine}, we use

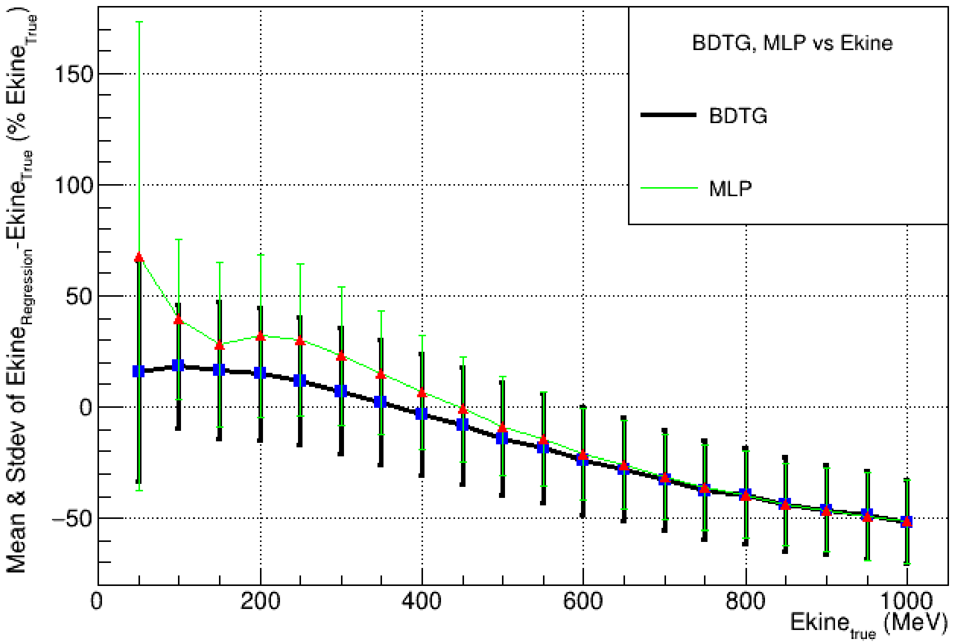
- $Layer_0$: 10 nodes (input features)
- $Layer_1$: 30 nodes (hidden layer)
- an output (E_{kine})



Results

BDTG ad MLP efficiently estimate the energy of the proton up to ~500 MeV. In higher proton energies the energy is underestimated mainly due to the similar directional energy deposition in the Si Layers.





Discussion

- We plan to improve the energy clustering algorithm:
  - ✓ Find local clusters which are due to the passage of the primary particle
  - ✓ Discriminate energy depositions due to δ-rays
- The above will enrich the data set with the events that now are excluded from the study:
  - ✓ include events with energy asymmetry close to one
- The MVA techniques based on Monte Carlo data can be used for efficient particle identification and kinetic energy determination.
- MVA techniques for particle identification do not depend on the GCR spectrum thus may be used for identifying fragmentation products

- *Next steps in the MC study*:
  - ✓ Kinetic energy determination for other particles
  - ✓ Inclusion of a spaceship model.

BACKUP SLIDES

BDTG parameters

		BTDG
Training Sample (Events)		20763
Testing Sample (Events)		20763
Max Trees		5000
Max Depth		5
Variable Granularity (nCuts)		50
Boost Type	**Bagging**	√
	BaggedSampleFraction	0.50
	Grad	√
Separation Type	**Gini Index**	
	Cross Entropy	
	Gini Index with Laplace	
	Mis Classification Error	
	SDivSqrtSPlusB	
	Regression Variance	√
Prune Method	No Pruning	
	Expected Error	
	Cost Complexity	√

MLP parameters

Neural Network Parameters	
Training Sample	20000
Testing Sample	4000
Number of Cycles	20000
Hidden Layers	26
TestRate	6
Training Method	BFGS
Sampling	0.3
Sampling Epoch	0.8
Convergence Improve	1E-6
Convergence Tests	15