Università di Pisa

Antiproton background rejection in the Mu2e experiment

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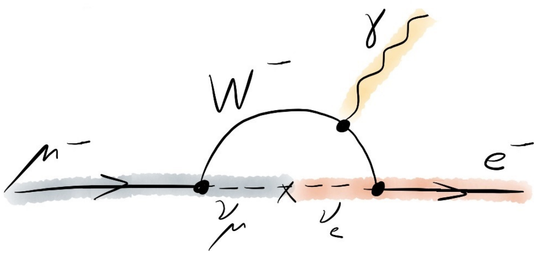
What is Mu2e

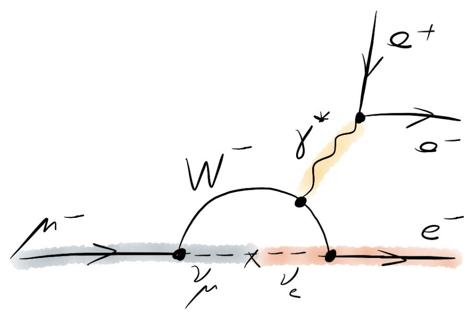
Mu2e is an experiment at Fermilab searching for Charged Lepton Flavor Violation

According to Standard Model, CLFV must occur at some level because of neutrino oscillations in processes such as

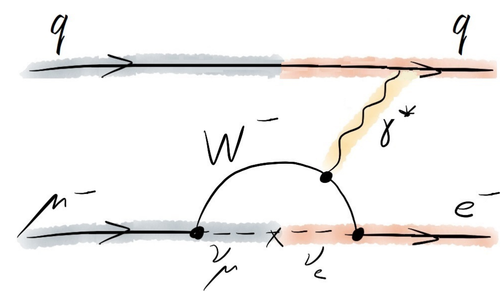
$\mu^- \rightarrow e^- \gamma$



$\mu^- \rightarrow e^- e^- e^+$



$\mu^- N \rightarrow e^- N$



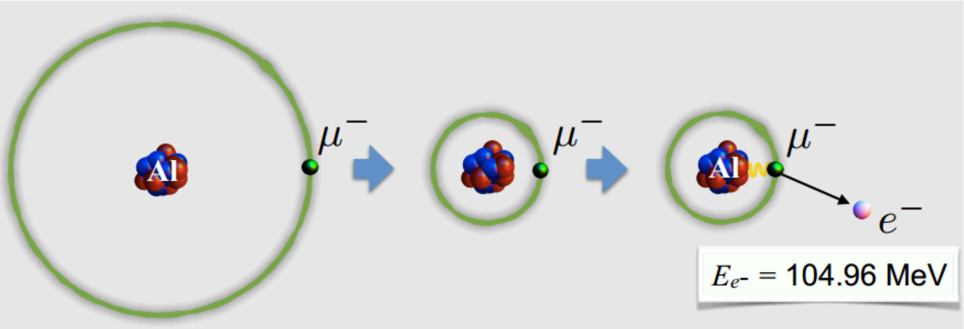
SM BR($\mu^- \rightarrow e^- \gamma$) $\approx 10^{-52}$ but Mu2e sensitivity $\approx 10^{-17}$

An observation of CLFV would provide us with proof of New Physics

The Experiment in Brief

Mu2e will look for the neutrinoless conversion of a muon into an electron in the field of an Aluminium nucleus:

$$\mu^- Al \rightarrow e^- Al$$



Experimental signature:

- Mono-energetic electron
- $E_e = m_\mu c^2 - E_{bind} - E_{rec} = 104.96 \text{ MeV}$

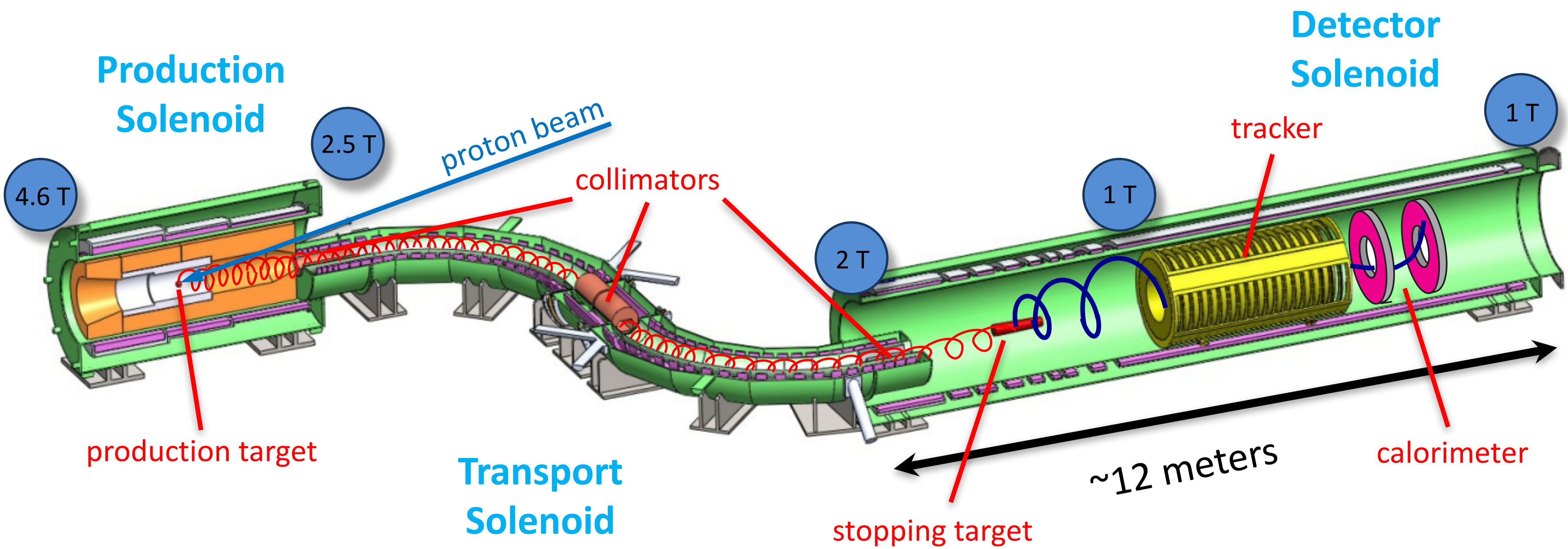
Mu2e will measure the ratio

Neutrinoless conversion events

$$R_{\mu e} = \frac{R(\mu^- Al \rightarrow e^- Al)}{R(\mu^- Al \rightarrow All\ \mu\ captures)}$$

Muonic capture events: $\mu^- Al \rightarrow \nu_\mu Mg^*$

Mu2e Apparatus



- A 8 GeV proton beam impinges on the production target
- The pions produced are collected and decay in flight (mostly into muons)
- The muon beam is stopped in the Aluminium stopping target
- Particles from the stopping target are detected by the tracker and the calorimeter

Why Antiproton Background

The proton beam energy is slightly above the antiproton production threshold ($pp \rightarrow ppp\bar{p}$):

$$s = 2m_p(m_p + E_p) = 16m_p^2 \qquad \Rightarrow \qquad E_p = 7m_p = 6.56\ \text{GeV}$$

Antiprotons may annihilate in the stopping target, eventually releasing 105 MeV electrons as secondary particles

BUT

~105 MeV is released in signal muon events
~2 GeV in background antiproton annihilations

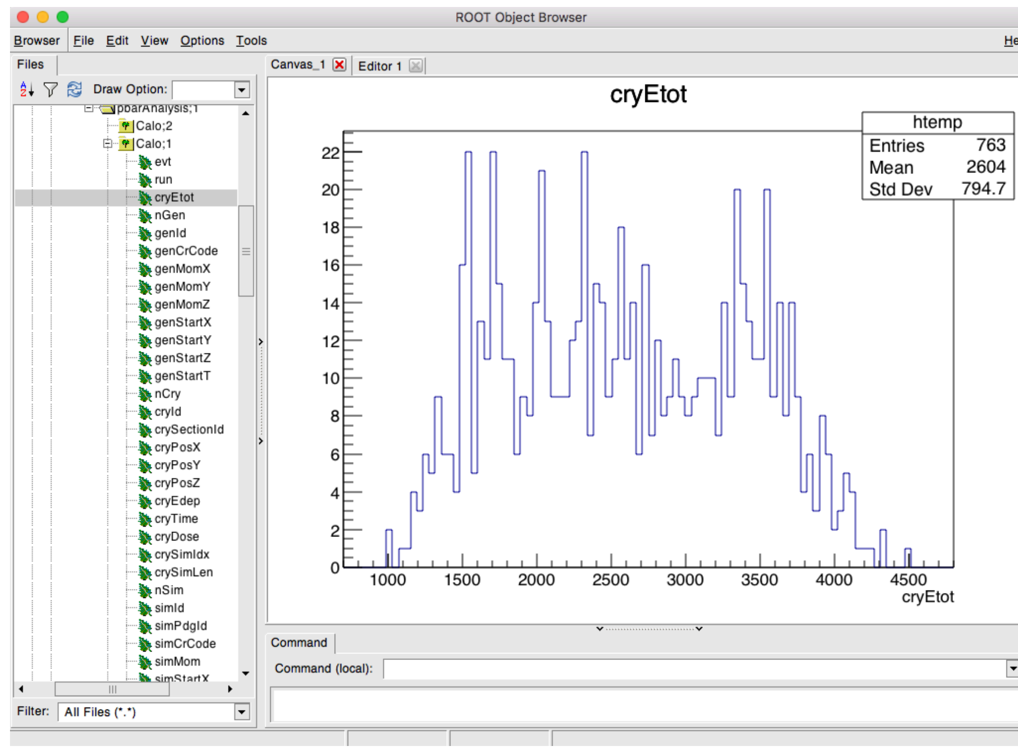
Goal: training a neural network through a machine learning algorithm to perform pattern recognition of signal and background events

Simulations

- To perform the task we simulate 40 million background events (antiproton annihilations in the stopping target) and 10 million signal events (neutrinoless muon-to-electron conversions)
- The information from both the tracker and the calorimeter is collected and analyzed in a ROOT environment

Not all the background events contain a fake signal electron

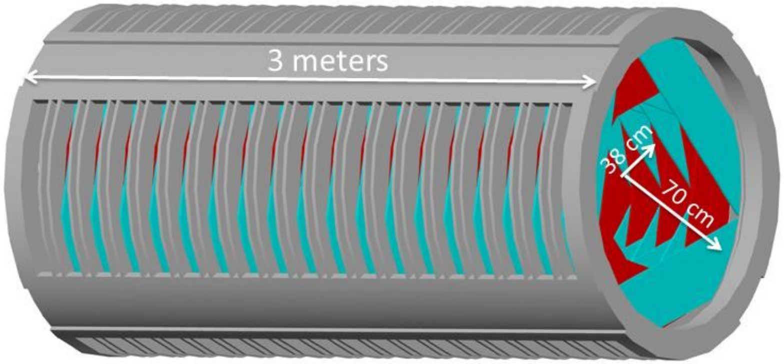
We need to get rid of the trivial background events by applying cuts on the information



The ROOT environment where the information is stored

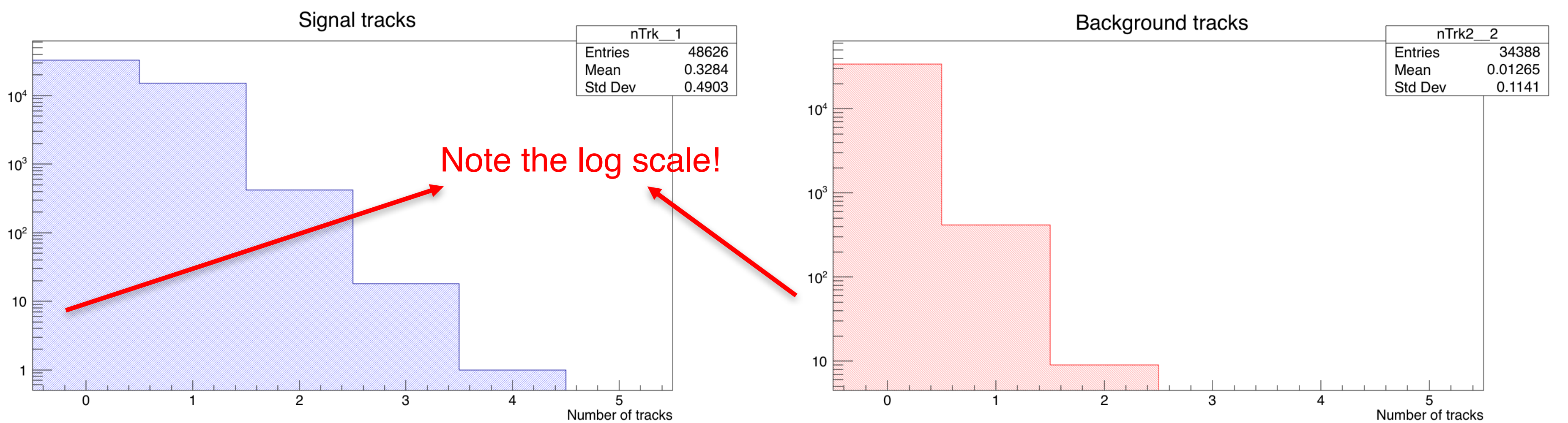
Tracks

The tracker is aimed to detect the tracks of the electrons, but it may happen that more than one possible track is reconstructed



The Mu2e tracker

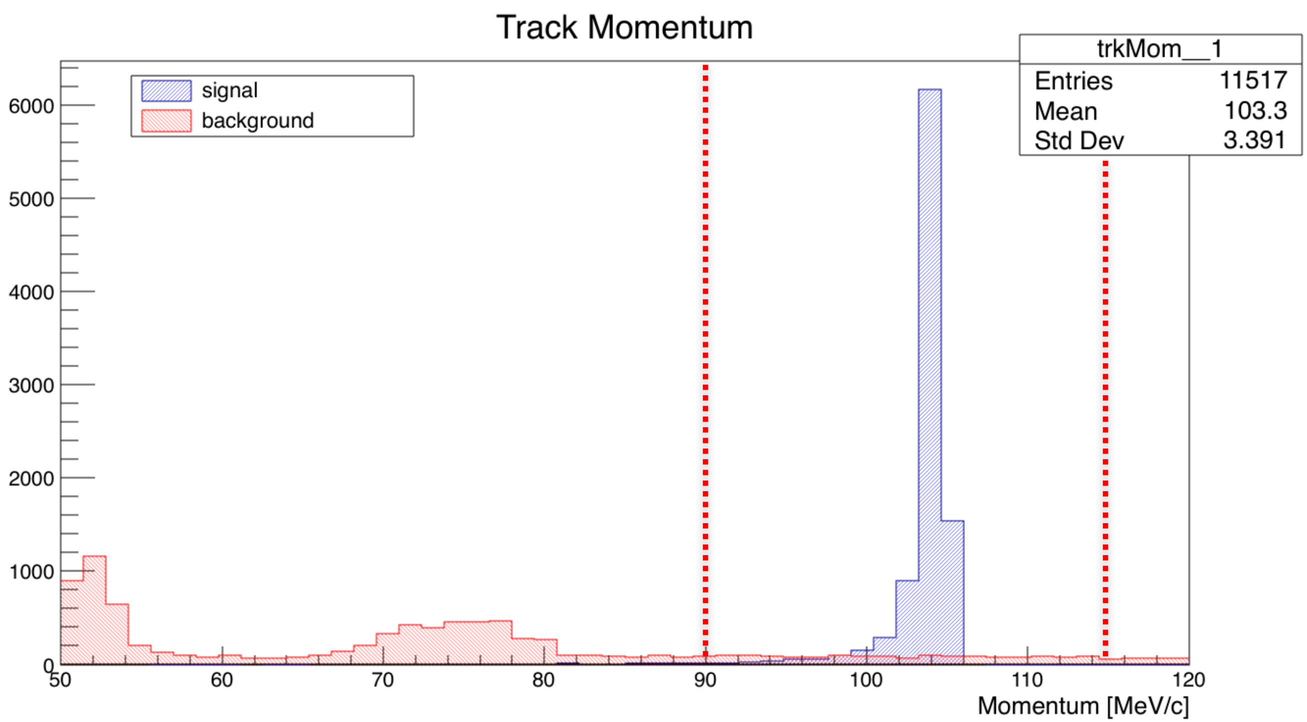
We should keep the events in which only one track is reconstructed by the tracker



Track Momentum

Whereas the signal is characterized by a mono-energetic 105 MeV electron, this is not true for the background

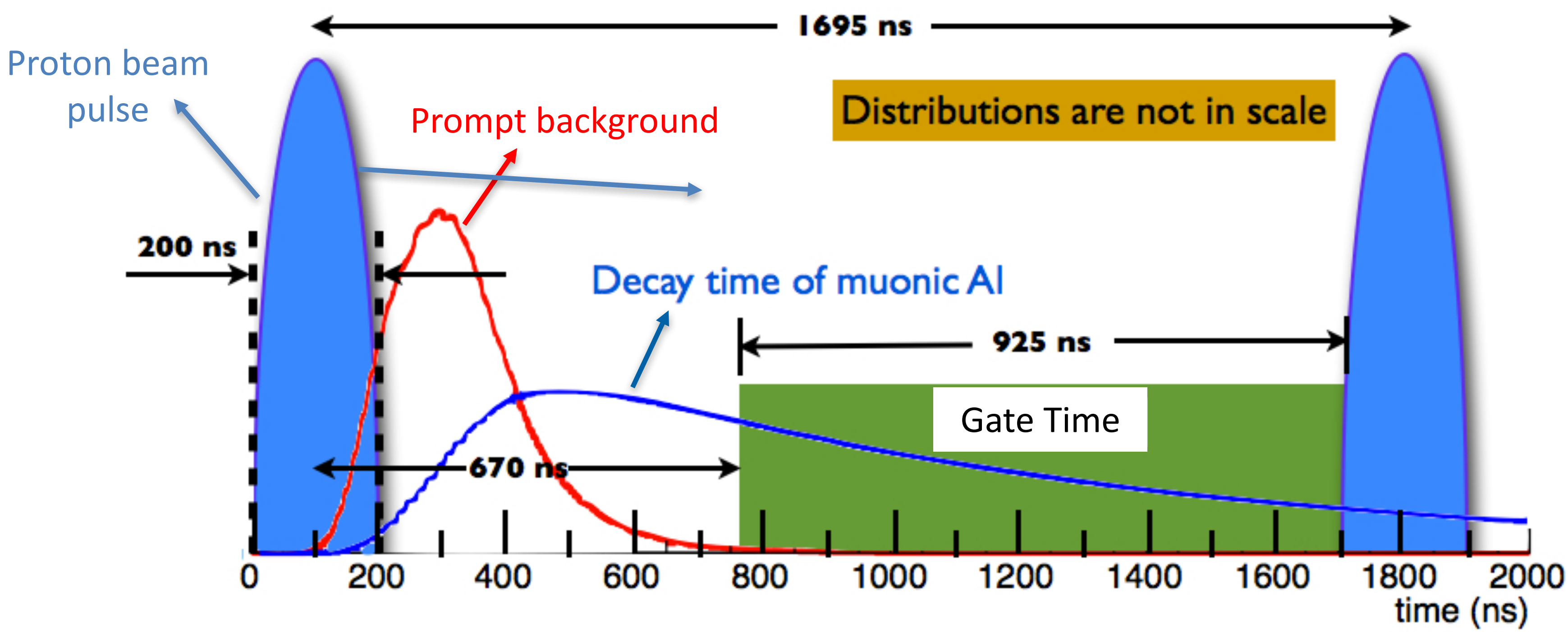
We can reject those events in which the track momentum is out of a certain range. We choose the track momentum to be between 90 MeV/c and 115 MeV/c



Gate Time

Mostly because of the pion contamination in the muon beam, we have a prompt background in the detectors. But pions' lifetime is much shorter than muons' one

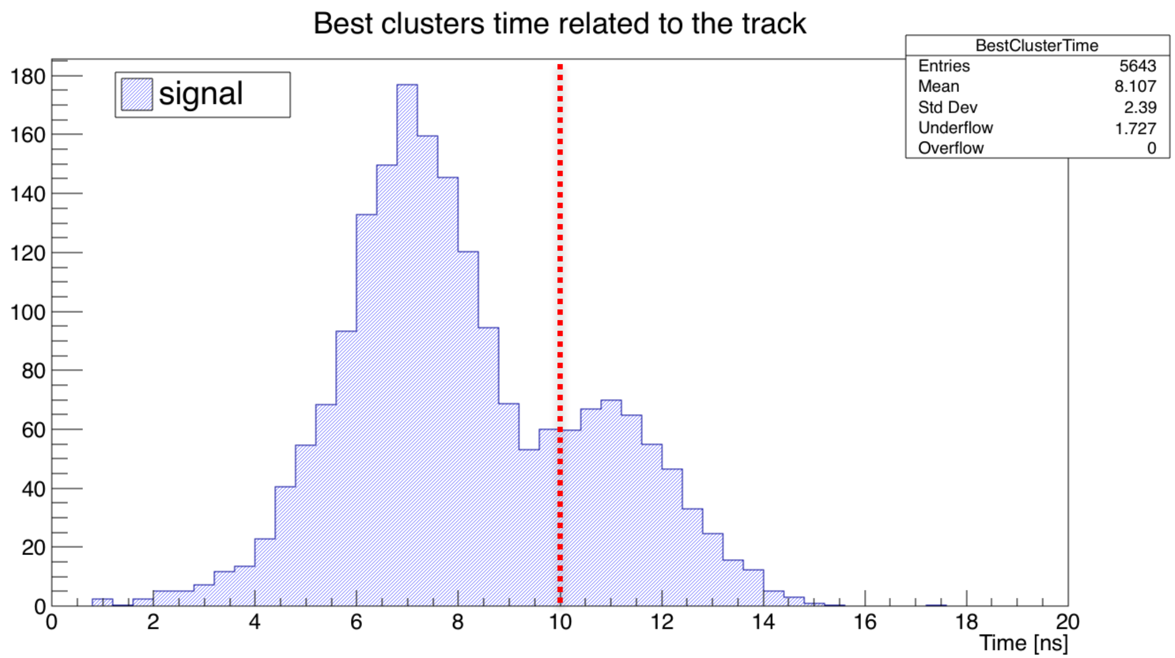
We can get rid of the prompt background by choosing a gate time open 700 ns after the proton beam pulse

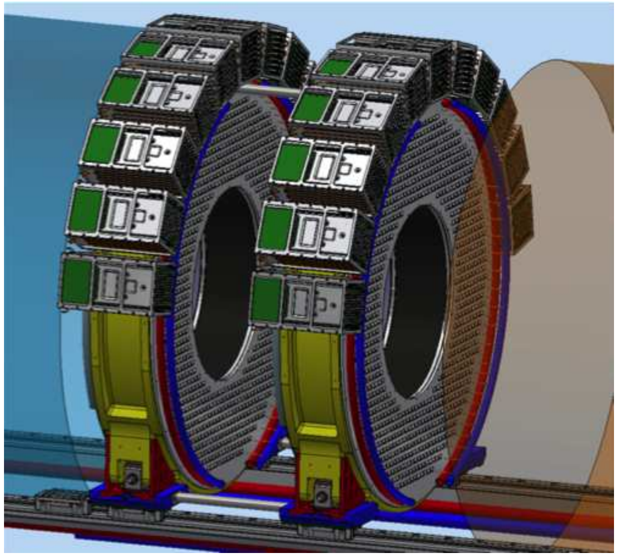


Selection of the Calorimeter's First Disk

Mu2e calorimeter consists of two disks. In our analysis we want to focus on particles hitting the first disk. Because of a bug in the software, the disk was not recorded, but rerun the events will take too long. To fix it we had this idea: if the particles hit the second disk, we expect it to happen later than the first disk, so that the time distribution of the clusters related to the track time shows two peaks

We can select the first disk by applying a cut on this time distribution (we select events earlier than 10 ns)



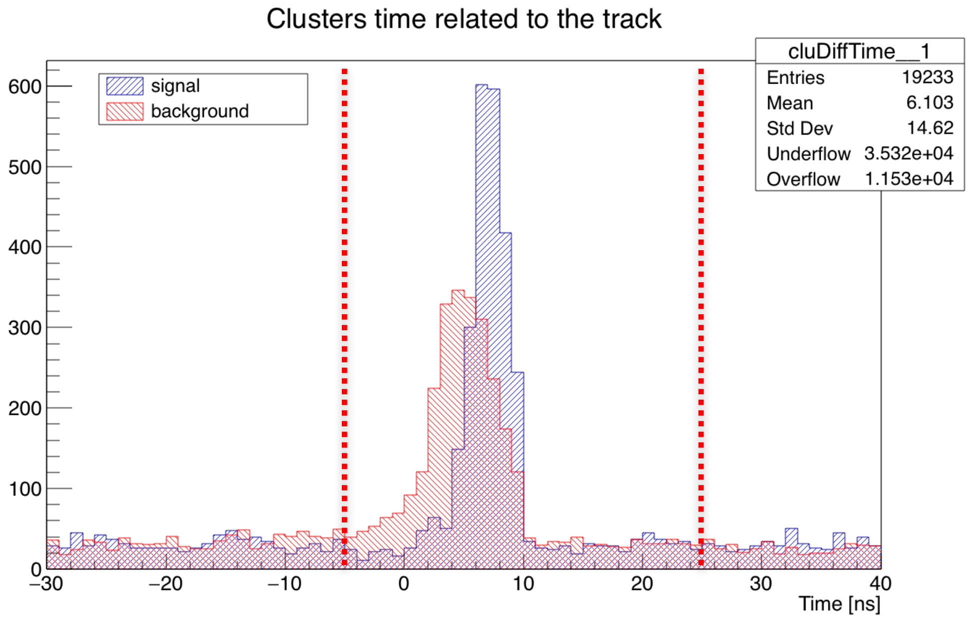


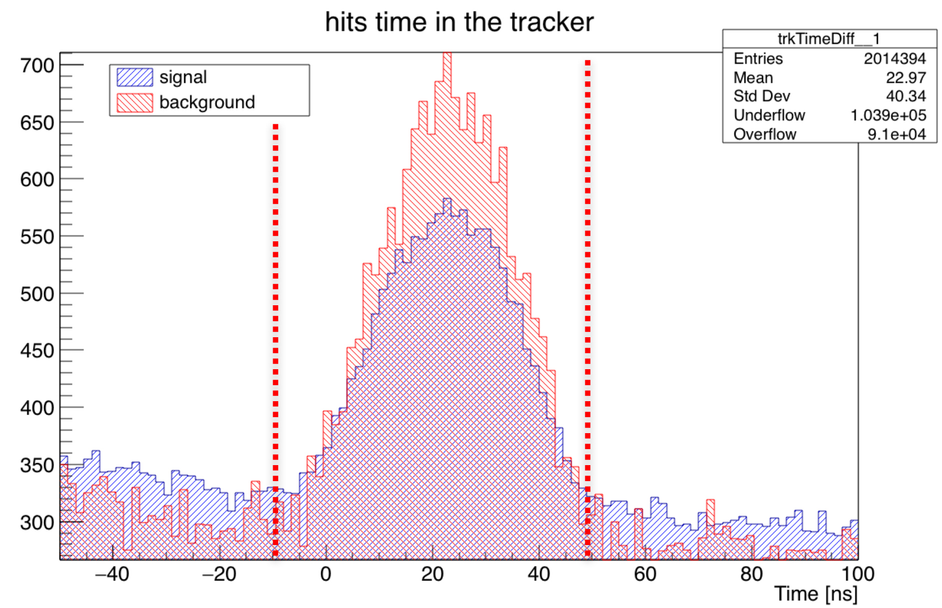
The Mu2e calorimeter

Selection of Clusters and Hits

Because of the detectors' random activity and noise, not all the information concerning the clusters and the tracker (hits in the straws, energy of the hits, etc) are related to the events we want to analyze. Anyway we expect there is more activity during the event

→ We can select the clusters and tracker hits by finding a peak in their time distributions related to the track





Particle Identification

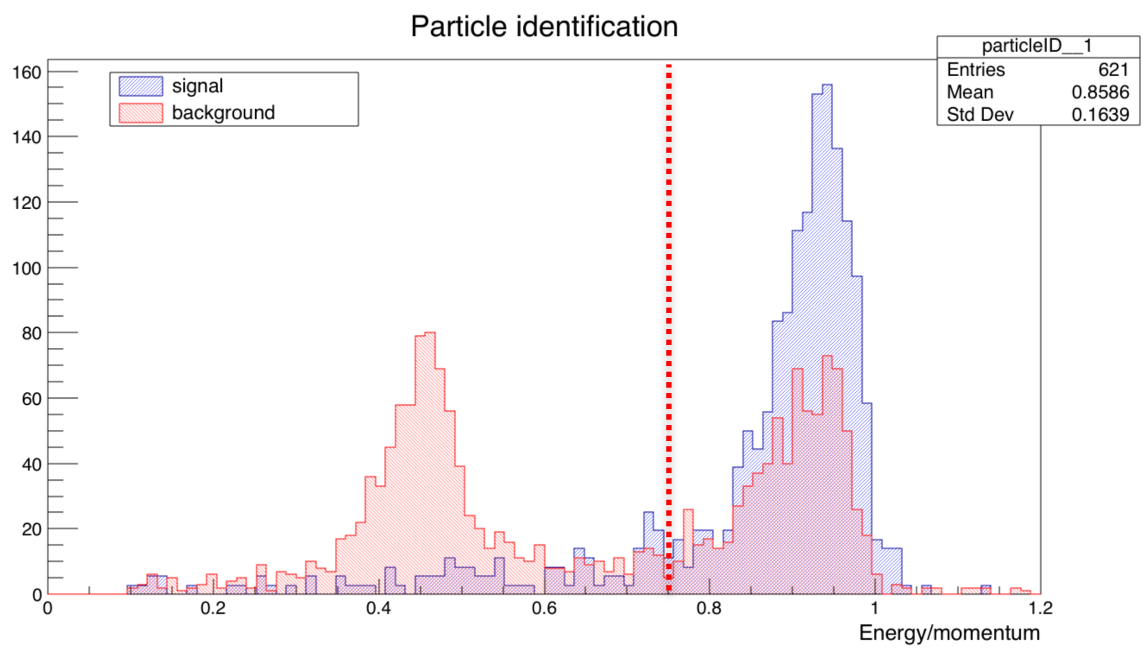
What if the clusters and tracks we are analyzing refer to muons and not to electrons? Let's suppose both particles release all their energy in the calorimeter and for both the momentum is 105 MeV/c:

- Muons: $T_\mu = E_\mu - m_\mu = \sqrt{p^2c^2 + m^2c^4} - m_\mu \approx 148 - 105 = 43\ \mathrm{MeV}$
- Electrons: $T_e \approx 105\ \mathrm{MeV}$

Muons: $\frac{T_\mu}{p} \approx 0.4$

Electrons : $\frac{T_\mu}{p} \approx 1$

We can perform particle ID by looking at this ratio. We reject events whose ratio is less than 0.75



Summarizing the Cuts

1. We want to make sure there is only one track
2. The signal is mono-energetic and we are interested in tracks whose momenta are between 90 Mev/c and 115 MeV/c
3. We want to get rid of the prompt background due to the beam contamination
4. We want the particles impinge on the calorimeter's first disk
5. We want to analyze only clusters (in the calorimeter) and hits (in the tracker) related to the event
6. We want to be sure that the particles we are dealing with are electrons, not muons

After the cuts

- ~ 2,000 left background events (we started with 40,000,000)
- ~ 800,000 left signal events (we started with 10,000,000)

Training Variables

An antiproton annihilation releases:

- More energy
- More particles in a shorter time

than a muon-to-electron conversion event. So we are interested in

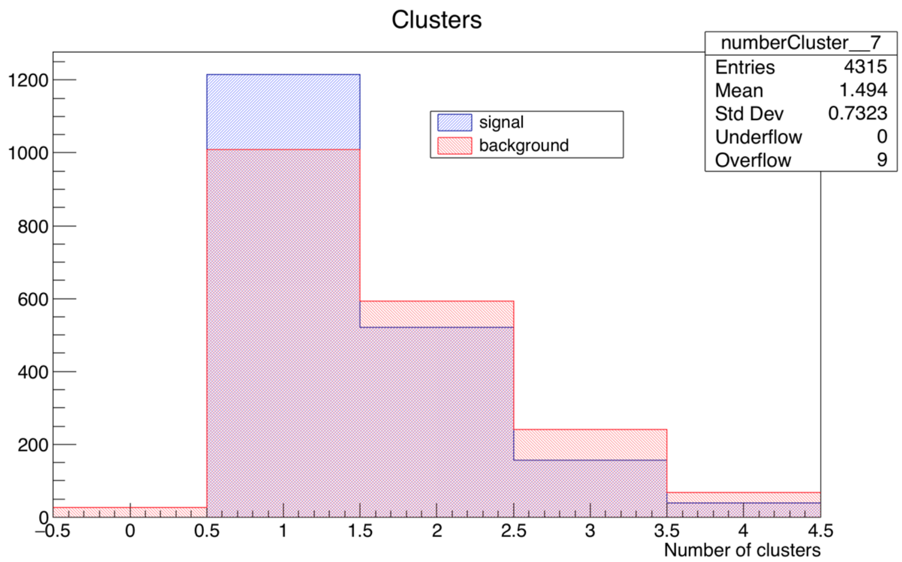
- The number of clusters in the calorimeter and hits in the tracker
- The clusters and hits energy
- The clusters and hits time

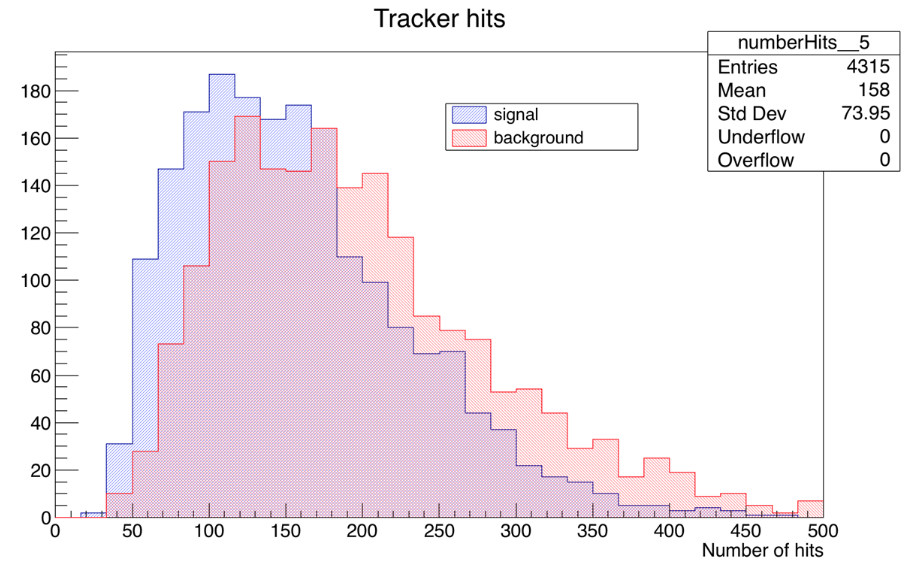
From the simulations we extrapolated the following interesting variables

Number of Clusters and Hits

Since an antiproton annihilation may release more particles, we want to look at the number of clusters and hits

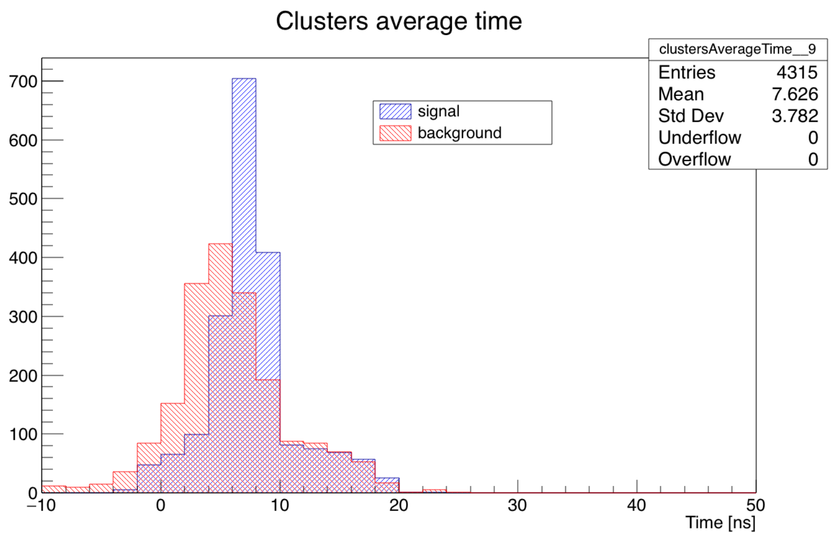
It seems that we have more clusters and hits for the background events than for the signal ones

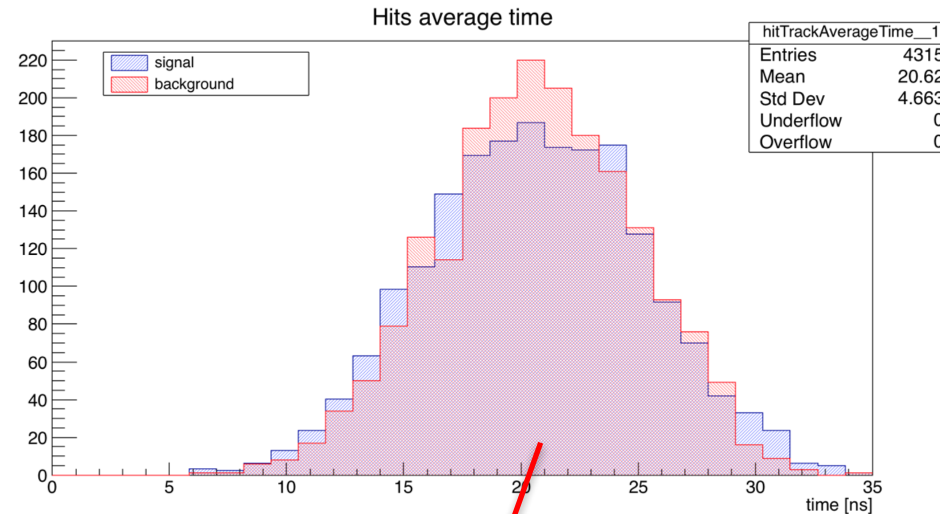




Clusters and Hits Time

Since the clusters and hits in the background events are related to the same phenomenon (antiproton annihilation), we may expect some differences in the time of the clusters and hits

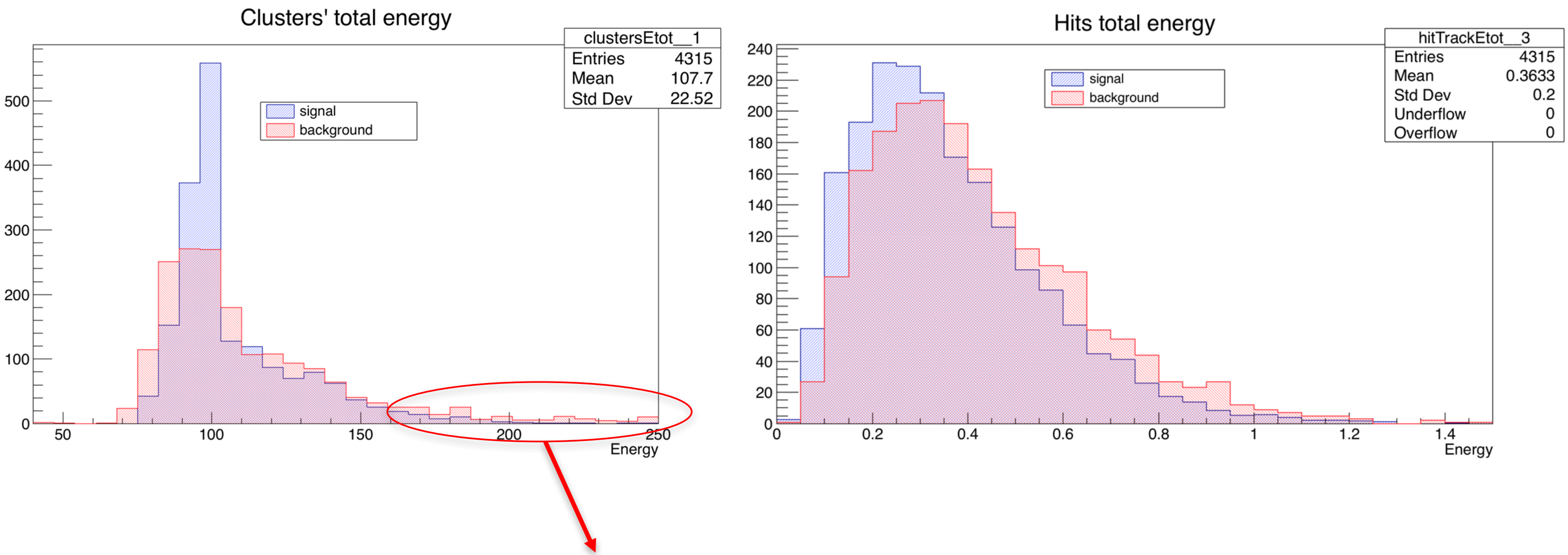




Not so many differences indeed

Clusters and Hits Energy

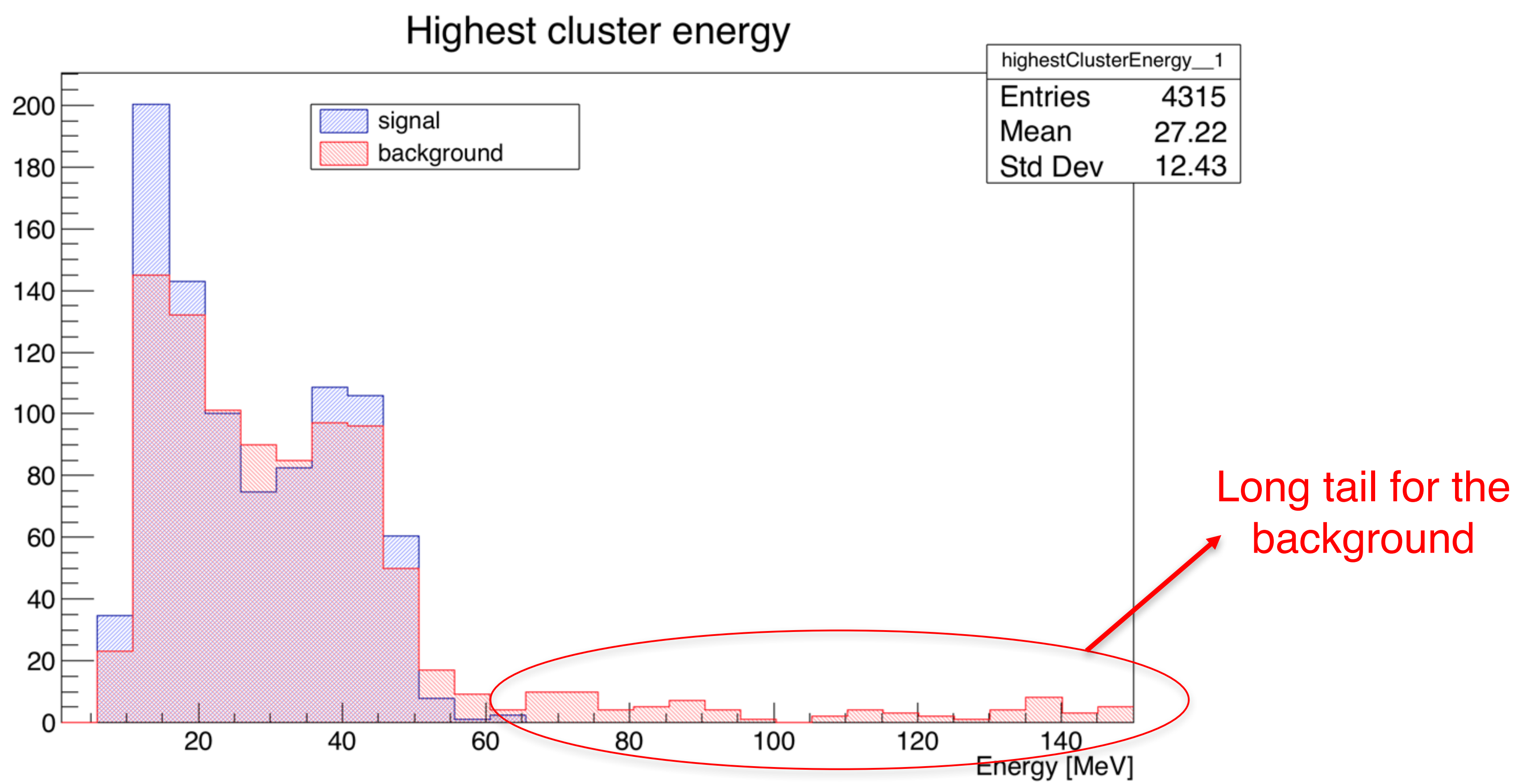
The energy released in a muon-to-electron conversion is ~105 MeV, much lower than the one in an annihilation antiproton (~2 GeV). We may wonder if the total energy of the clusters and hits is different for both the events



Long tail for the background clusters

Clusters Highest Energy

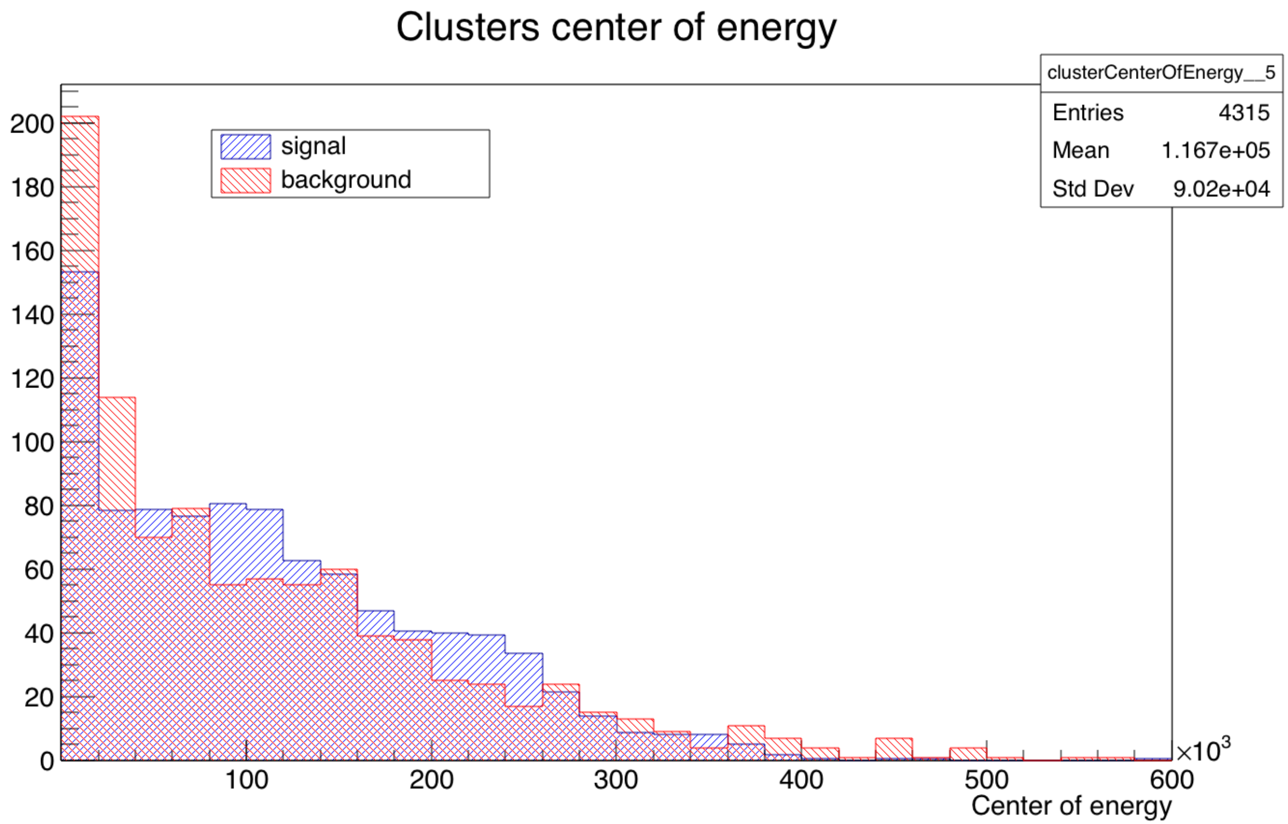
We also analyzed the highest energy of the clusters not related to the track. Since more energy is released in an antiproton annihilation, we expect to find higher energy clusters in these events



Clusters Center of Energy

We then looked at the “center of energy of the clusters”, defined as

$$\frac{\sum_i r_i^2 E_i}{\sum_i E_i}$$



Neural Network Training

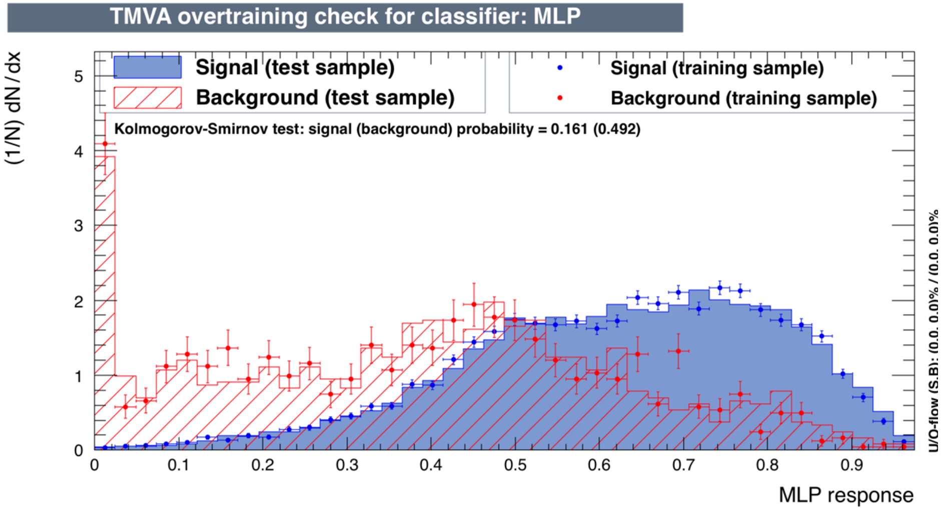
- ROOT provides a MultiVariate Analysis Package (TMVA) to train and test neural networks

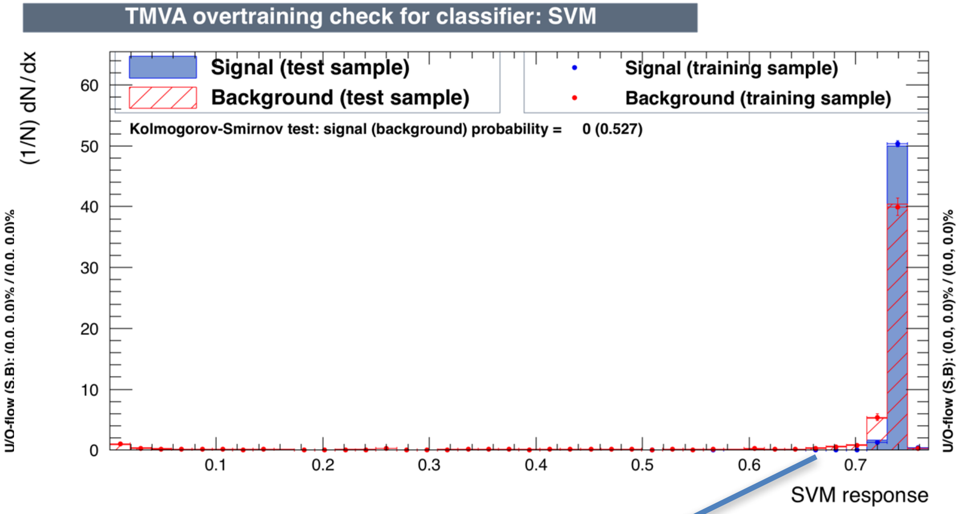
- It also provides different training methods, with different features

- The methods we want to use for our training are
  1. Boosted Decision Tree (BDT)
  2. MultiLayer Perceptron (MLP)
  3. Support Vector Machine (SVM)

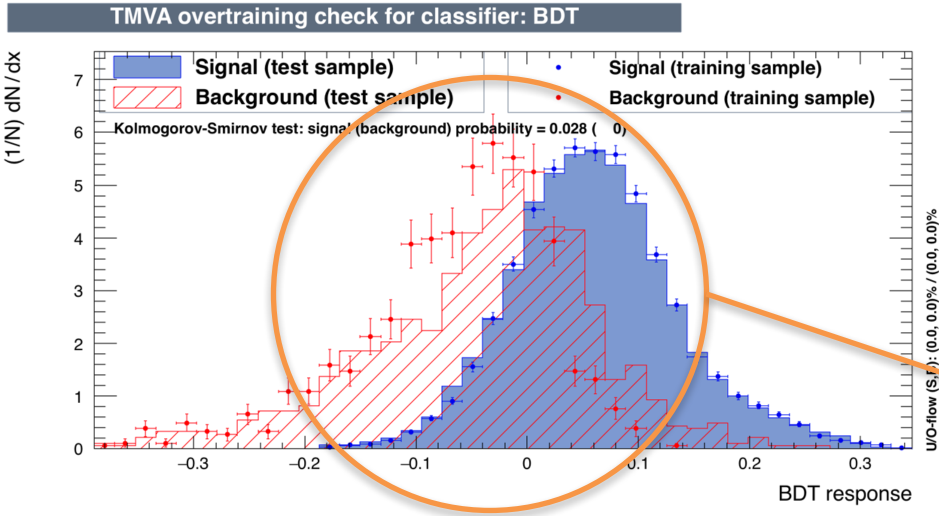
- We are now ready to train our Neural Network

Output Distributions



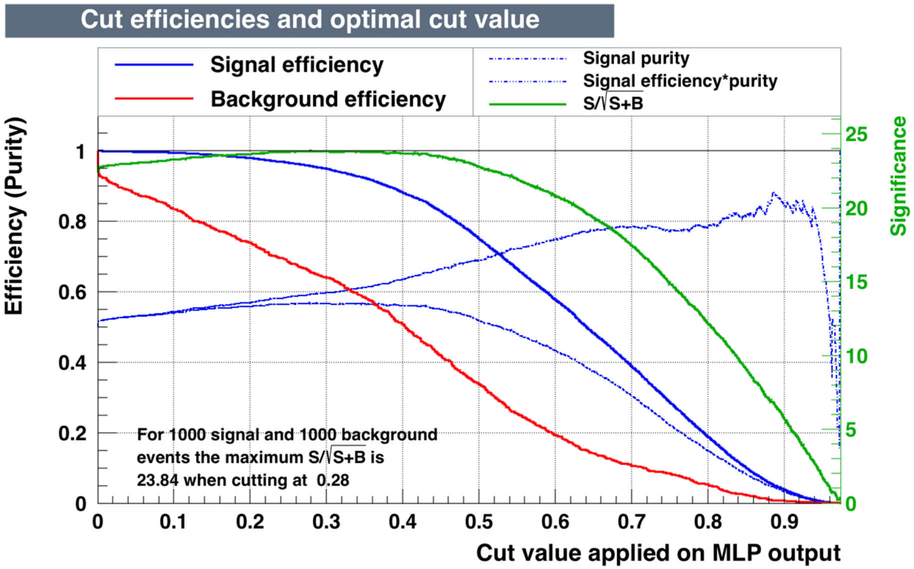


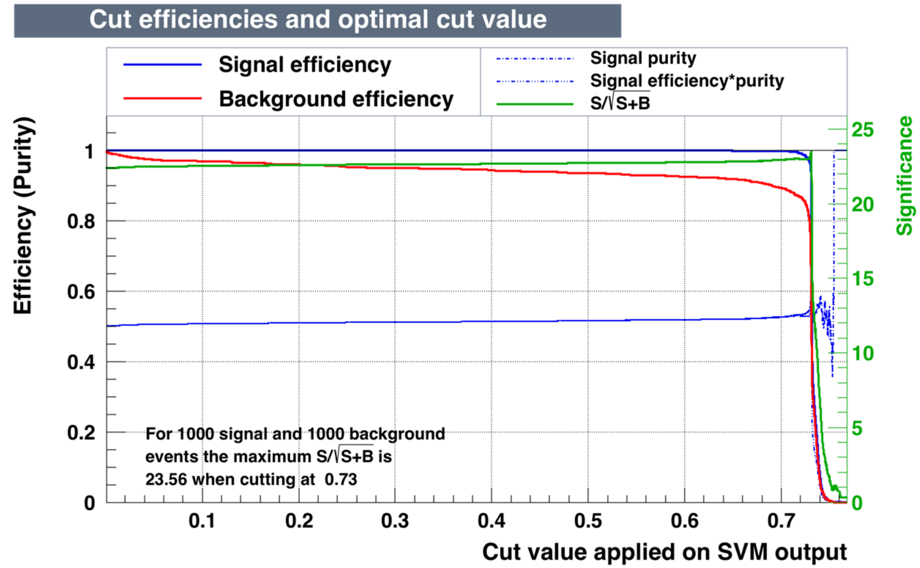
Not such a good discriminating power

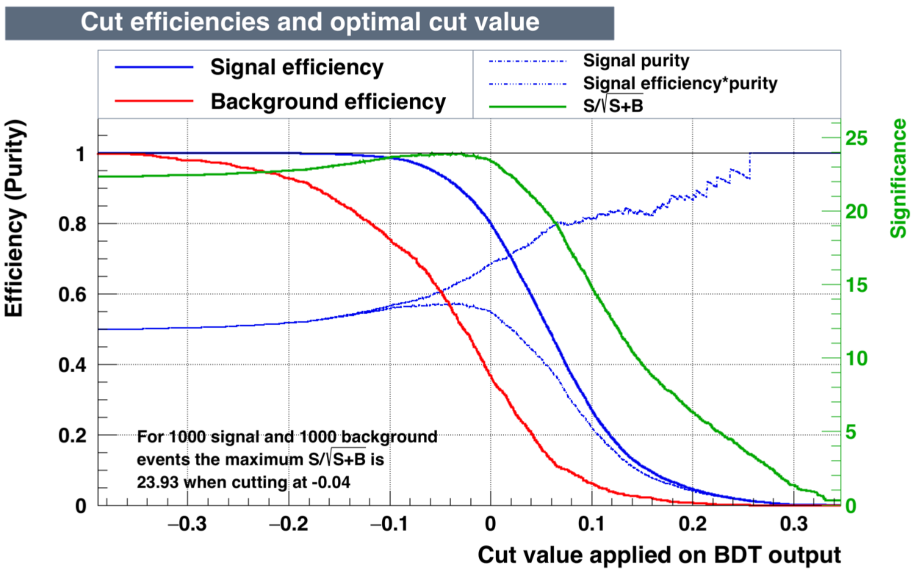


Overtraining!!! Probably too few background events…

Cut Efficiencies

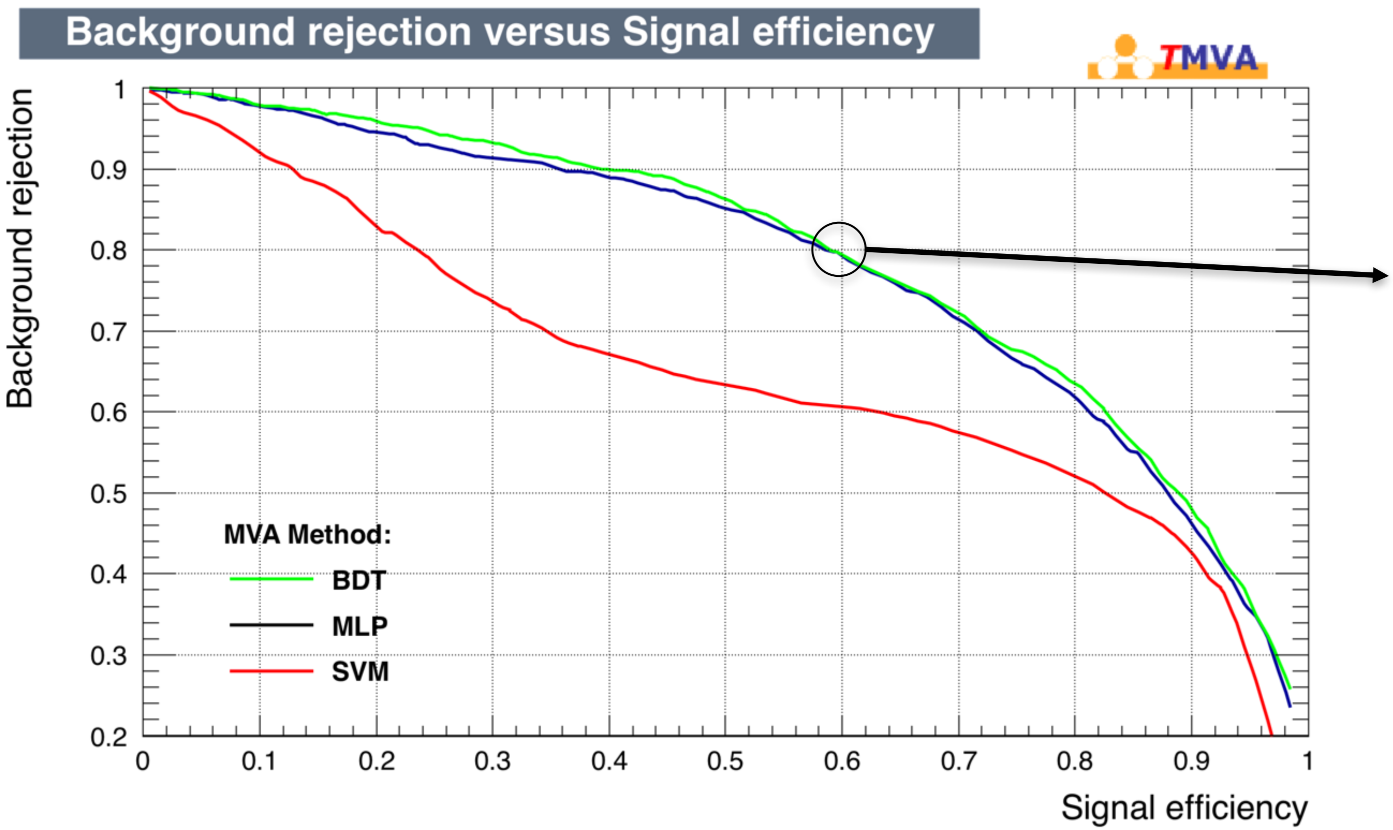






These plots show the signal and the background efficiency as a function of the output value for each training method. Every plot also provides the output value which maximizes the ratio $S/\sqrt{S+B}$

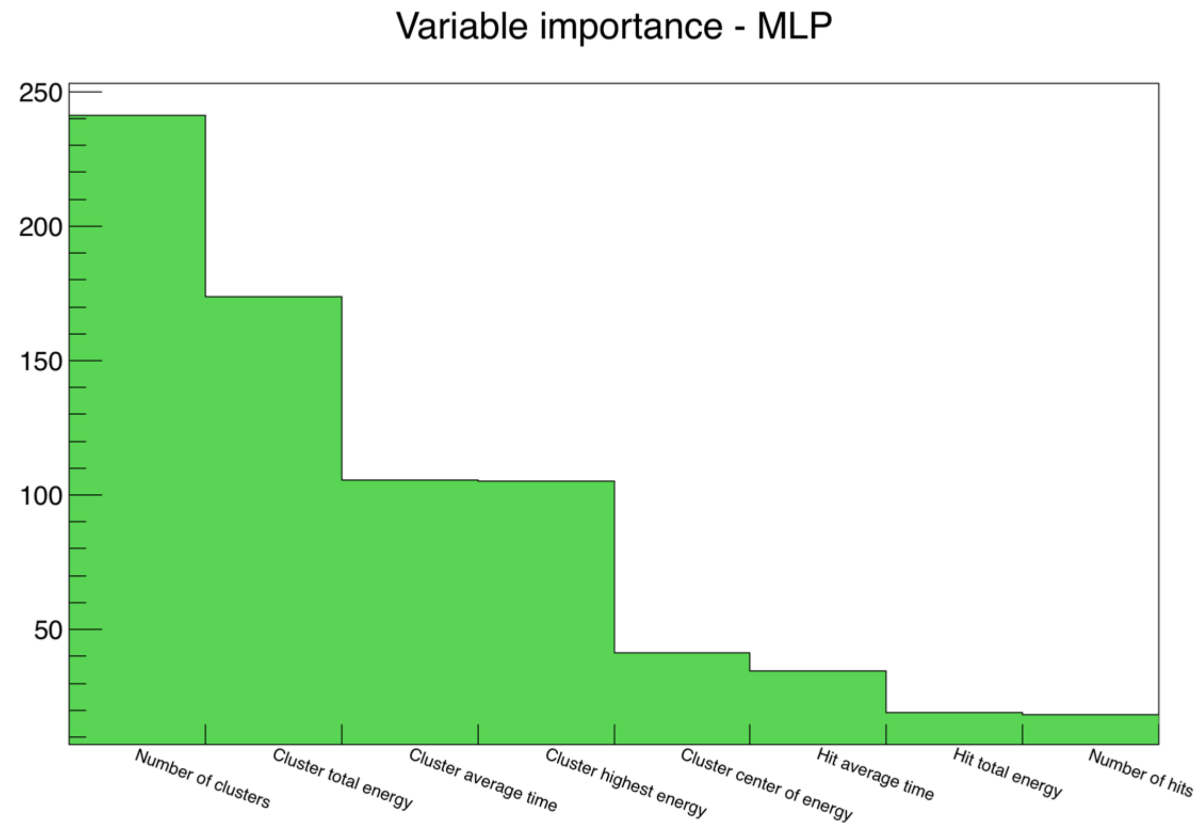
Background Rejection and Signal Efficiency



MLP can reject 80% of the background and keep 60% of the signal

- SVM didn’t do a good job, as we expected
- BDT is overtrained, as we have already realized
- MLP hadn’t these problems and performed a good job

Variable Importance



The plot shows the importance of the variables in training the neural network for MLP. The calorimeter variables result to be the best ones. In particular, the number, energy and time of the clusters are the most powerful variables.

Conclusions

- Two of the three training methods used in this job (SVM and BDT) are not so good. Probably we need more statistics to avoid ovrtraining and to reduce the statistical fluctuations in the data sample
- MLP achieves a good compromise between the background rejection (80%) and signal efficiency (60%)
- The result of this job is not too different to the previous ones

To improve this job we should

- Have more statistics, but running a simulation to find one fake signal in a background event will take much time
- Probably add more variables to train the network

Thank You!

I wish to thank all those who made this internship possible and enjoyable:

- the organizers, Simone Donati, Giorgio Bellettini and Emanuela Barzi, for giving me the opportunity to attend this summer school and to work as a real physicist,
- my supervisor, Robert Bernstein, for introducing me into the experiment, for his teachings and for his patience with me,
- my new friends, for sharing this experience with me and making it unforgettable.

Many thanks to you all!!!