# Muon Scattering Tomography with Resistive Plate Chambers

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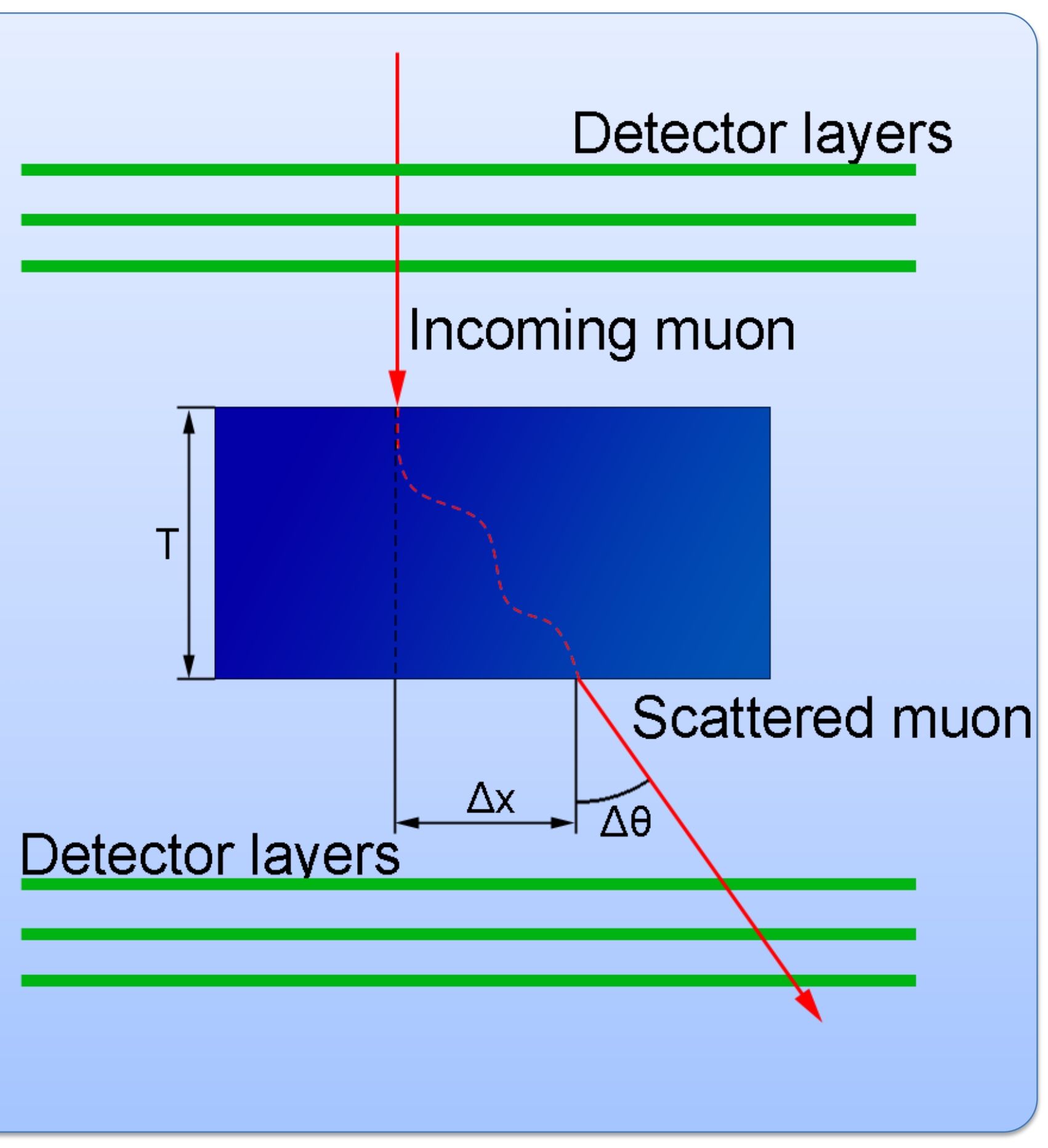
## The idea

Muon scattering tomography (MST) exploits natural cosmic radiation to provide information about the content of an unknown object. Muons that reach the Earth's surface can penetrate matter but may interact with it, undergoing multiple Coulomb scattering, so that their original direction is changed. The scattering angle distribution can be approximated with a Gaussian curve [1] with variance $\sigma^2_0$ which depends, among other parameters, on the length of radiation $X_0$ (eq. 1). $X_0$ can be expressed as a function of the atomic number (Z) of the interacting medium (eq. 2) [2].

Since high-Z materials are more likely to produce large scattering angles θ, the muons trajectories can provide information on the materials which have been traversed. In MST a sample is analyzed by collecting data on how cosmic rays scatter through it and using these data to construct a tomographic image. Alternatively, it is possible to study the scattering distribution to evaluate, within a confidence interval, whether the sample contains zones of anomalous scattering.



## Why use cosmic ray muons?

- They are always available, with flux of ~100 Hz/m$^2$ and energies from 0.1 GeV to 10 GeV.
- They are virtually impossible to screen against as dE/dx ~ 2 MeV·g$^{-1}$·cm$^2$ for 1 GeV muons.
- They are charged and can be easily detected.
- There is no radiation hazard for the scanner operators.
- MST is undetectable by the object being scanned, since no extra radiation is introduced.

**These features make MST a useful technique in applications related to homeland security [3].**

$$\sigma_0^2 \approx \left(\frac{15\ MeV}{pc\,\beta}\right)^2 \frac{T}{X_0} \qquad (1)$$

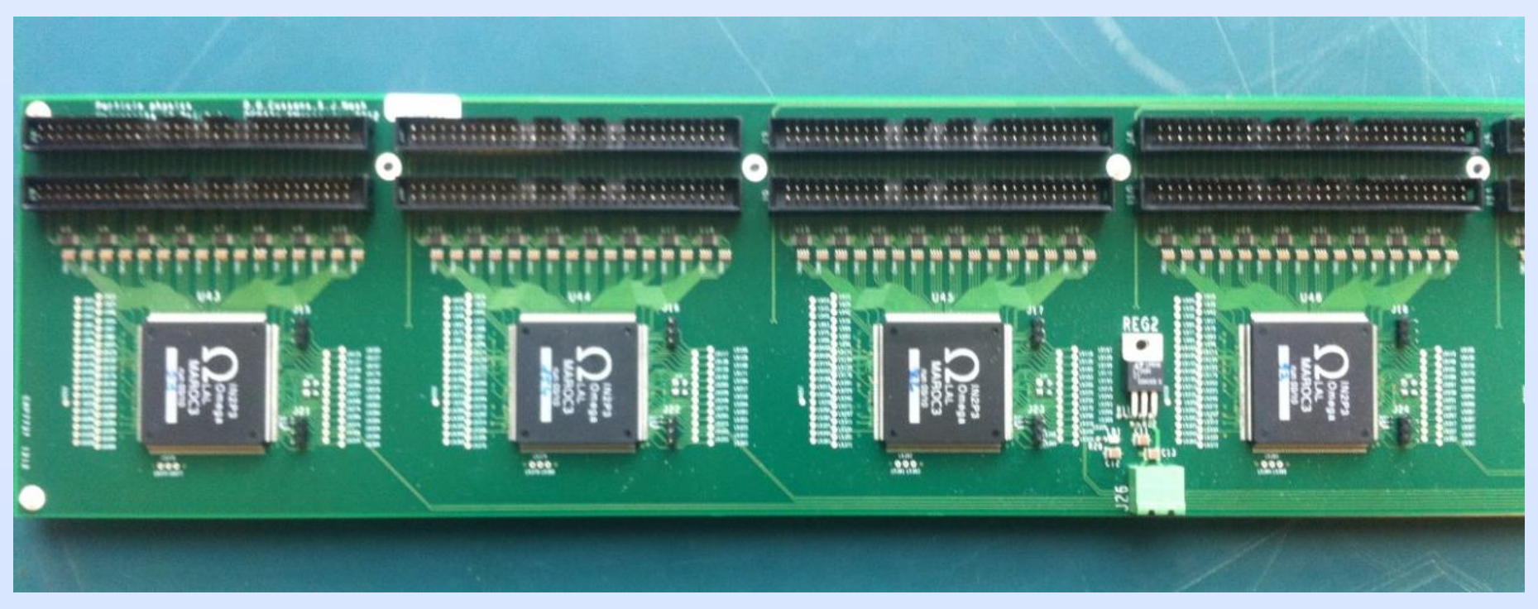
$$X_0 \approx \frac{A \cdot 716.4\, g/cm^2}{\rho \cdot Z \cdot (Z+1)\ln(287/Z)} \qquad (2)$$

## Detector

Muons can be easily tracked by means of gas detectors such as the resistive plate chambers (RPC).

RPCs are widely used in high energy physics experiments to detect charged radiation and have several interesting features:

- affordable price per unit area
- ease of scale-up to cover large areas
- high detection efficiency (> 95 %)
- self-triggering capability
- rugged build
- good time resolution (~ 1 ns)
- good spatial resolution (< 1 mm)



*A section of the readout board, which uses five MAROC3 chips read-out by a Xilinx xc6slx16 FPGA*

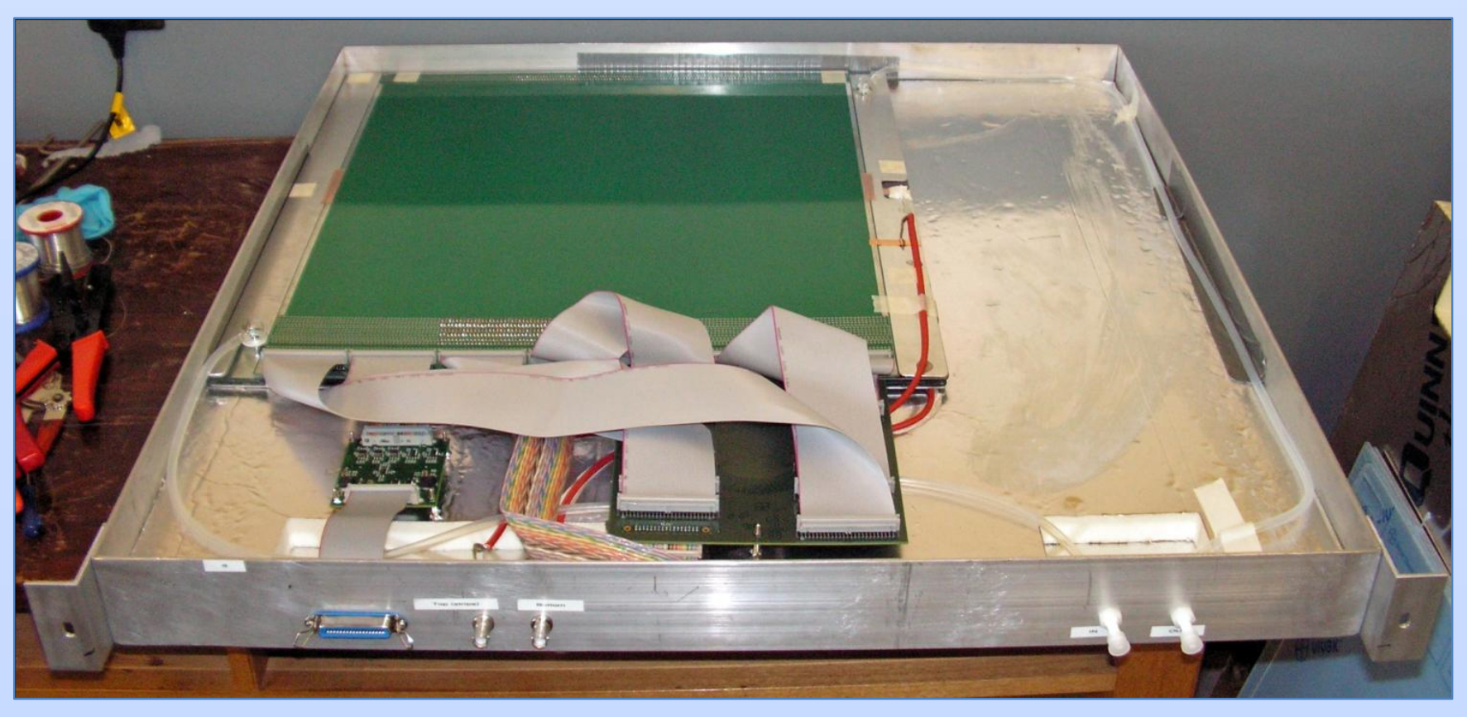
## The setup

Our prototype uses RPCs with an active area of 0.5 x 0.5 m$^2$. The gas mixture (freon 95 %, isobutane 5 %) is introduced to a 2 mm gap between glass plates (2 mm thickness) and maintained in an electric field of 600 V/cm by means of high voltage applied to a resistive coating (R~ 10$^5$ Ω/□).

The signal induced by gas ionization and charge avalanche is collected on pickup strips with 1.5 mm pitch.

Two RPCs and their front-end electronics are hosted in a metallic cassette which represents one detection layer. One RPC is rotated 90° with respect to the other to provide X and Y track information on each layer.

Six cassettes are inserted in a metallic rig which serves as mechanical support and includes the gas mixing system and the high voltage distribution.



*A cassette containing an RPC: the pickup board is connected to the readout board (on the right) via flat cables.*

*The setup with all detectors installed. The six cassettes are divided into two groups, between which the test sample is held on a wooden plate. The gas mixing system is visible on the bottom, with lines for isobutane, freon, argon and sulfur hexafluoride.*

## Readout chain

To cope with the high number of readout channels (>300 strips per RPC layer) the signals are read out using chips with a large number of channels. Originally HELIX chips [4] were used but these are being replaced by MAROC3 chips [5], which were originally developed for multi-anode photomultipliers in high energy physics experiments. The chips have 64 input channels with fully programmable low-noise charge amplifiers and shapers, together with a 8,10,or 12 bit Wilkinson ADC

In our system five MAROC3 chips are mounted on a PCB which is read out using a COTS module based around a Xilinx xc6slx16 FPGA.

The signal on the strips is sampled and digitized in response to a trigger signal. The trigger can either be generated by the MAROC3 chips or supplied from an external trigger based on scintillation detectors.

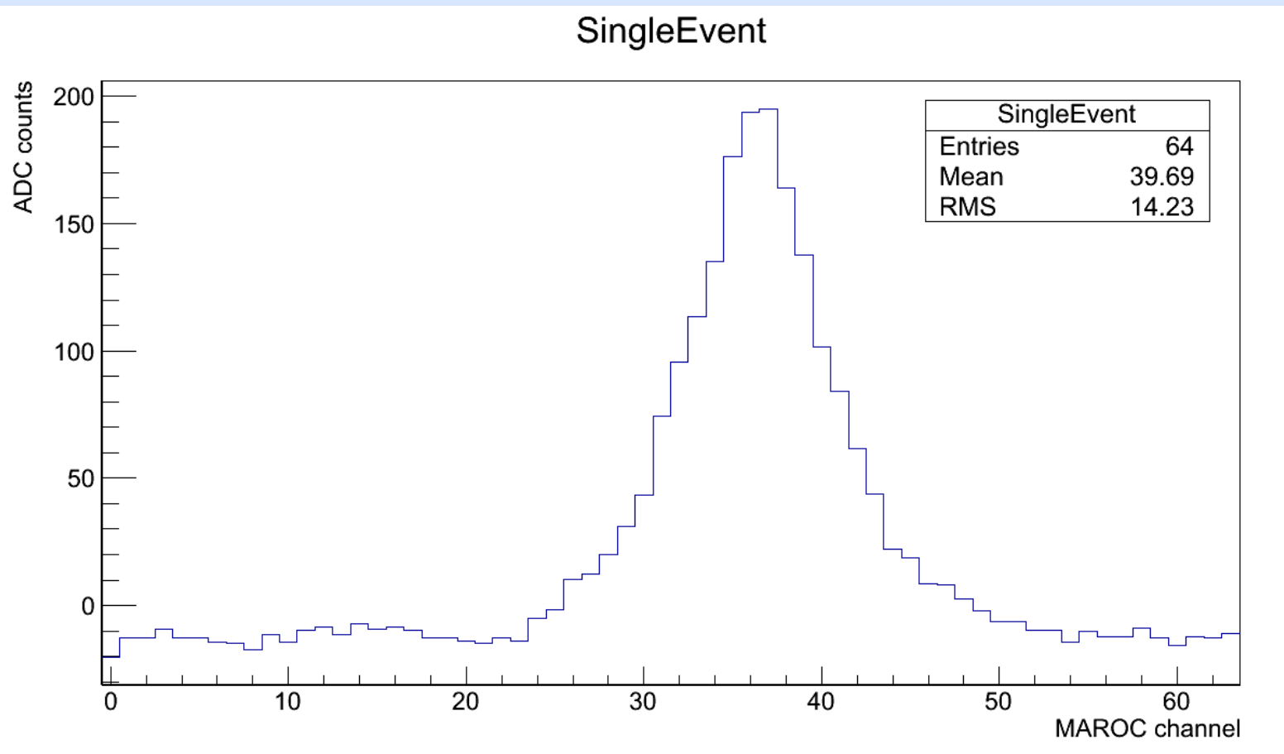
If internal triggering is used, the hits on different detector planes are combined to form a track based on a 40MHz time-stamp.

## Position Estimation by Fitting to Charge Distribution

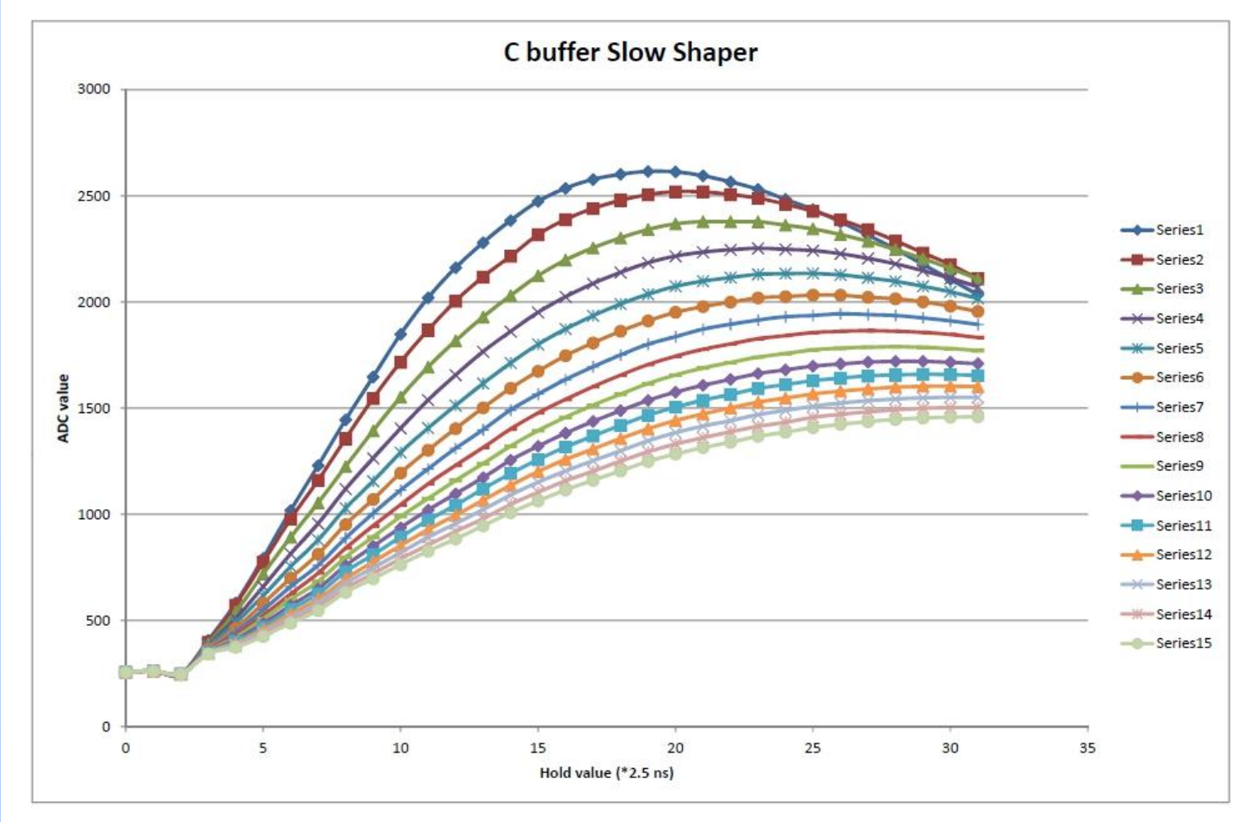
RPC detectors have traditionally been used with a coarse readout pitch, where the charge induced the passage of a particle is deposited almost entirely on one readout channel. However, but using a finer segmentation and distributing the charge over many pickup strips it is possible to obtain a spatial resolution better than 500μm [6]

### Trigger Generation and Signal Sampling

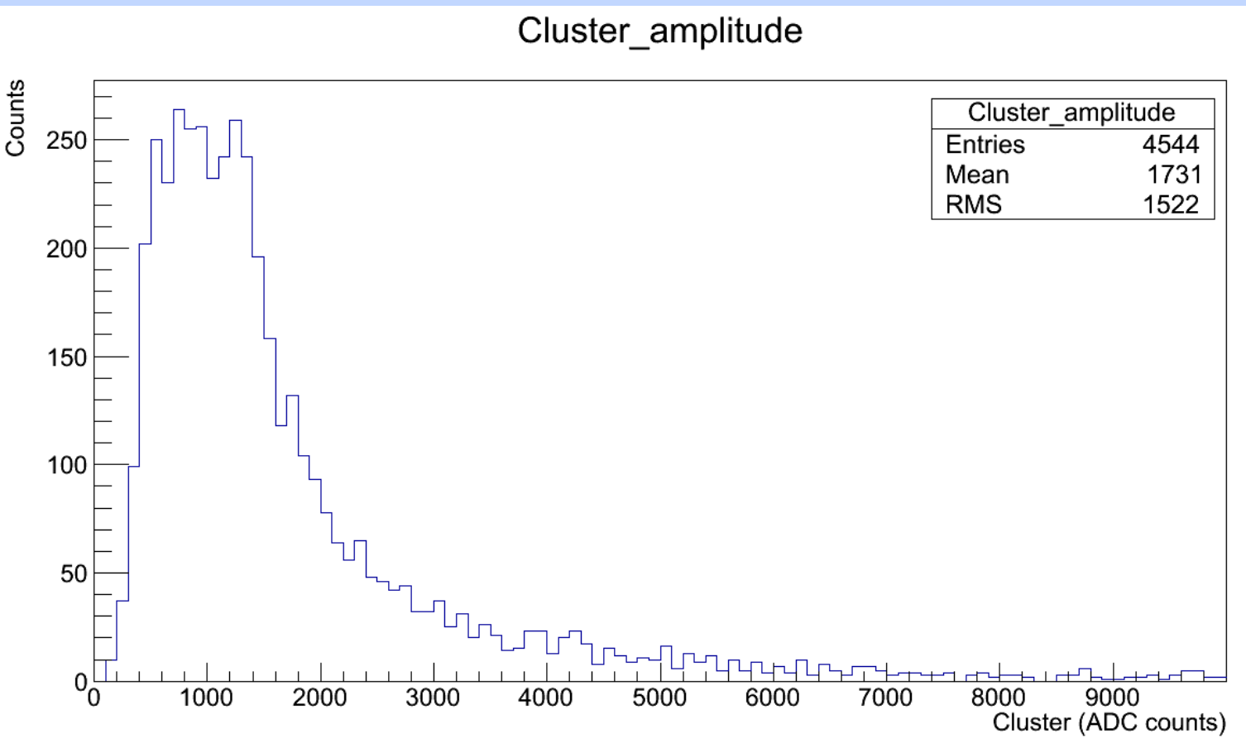
The MAROC3 has a threshold discriminator on each input coupled to a fast amplifier. These can be programmed to produce a trigger. It also has a shaping amplifier with an adjustable shaping time followed by a sample-and-hold circuit. Hence a trigger can be generated that samples the output of the shaping amplifier at the appropriate time



*A single hit readout from a 1.5mm pitch RPC with MAROC3 in 12-bit ADC mode.*



*ADC response to test-pulse as a function of delay between pulse injection and sample hold, for different shaping times*



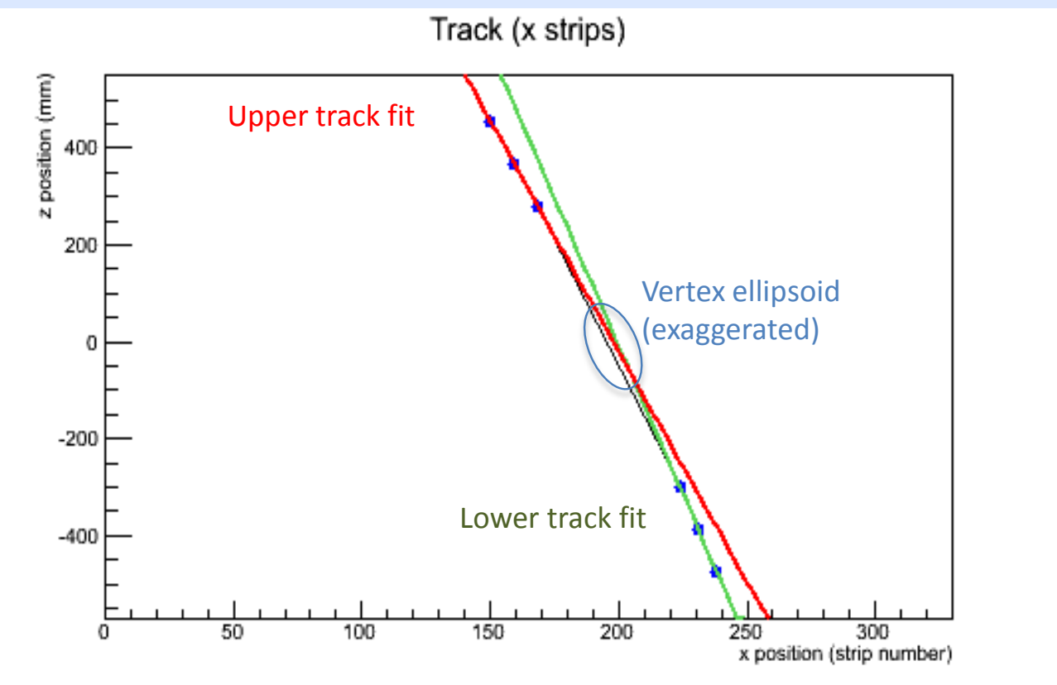
*Integrated charge over clusters. Using external scintillator trigger. Pedestal subtracted. ADC units*

## Threat detection by "decision variable"

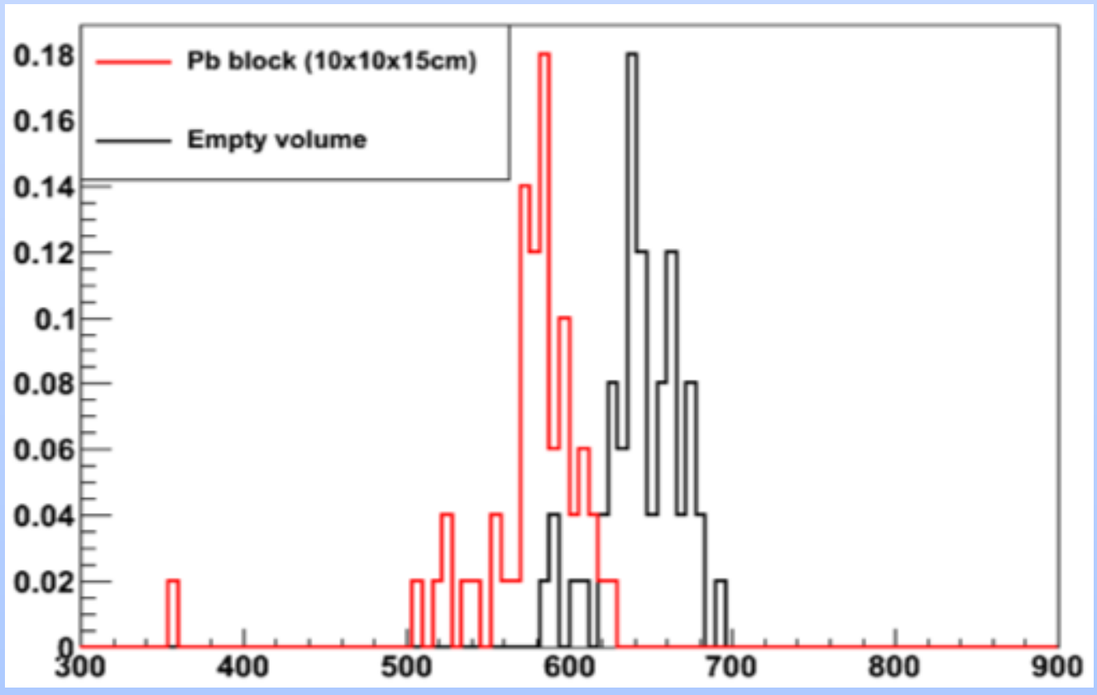
An approach is being developed at Bristol University which combines information from all muon tracks into a decision value by which to separate high-Z signal from low-Z background.

### Kinematic variables

From a combined track and vertex MINUIT fit [7], kinematic variables pertaining to the scattering behaviour are obtained (the scatter angle, track $\chi^2$ values, vertex uncertainty ellipsoid shapes). These variables are fed into TMVA [8], a toolkit for performing multivariate analysis, and result in a "Uranium-likeness" value for each track.



*Muon track fit in the XZ plane (real data).*



*Decision variable for lead vs. empty cabinet on real data for ca. 1 min of cosmic muons (real data).*

### Topological information

Since vertices from high-Z material tend to be clustered more closely together, a vertex metric value is calculated from the sum of metric distances of all vertices. This value is then weighted by the TMVA output. The median of the histogram of this value for the set of tracks under investigation is then used as the decision variable. This allows us to separate between signal and background on real data with ~92% efficiency at ~92% purity.

**References:**

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