High resolution muon tracking with resistive plate chambers for detection of special nuclear material

CHEF 2013 – Calorimetry for High Energy Frontier

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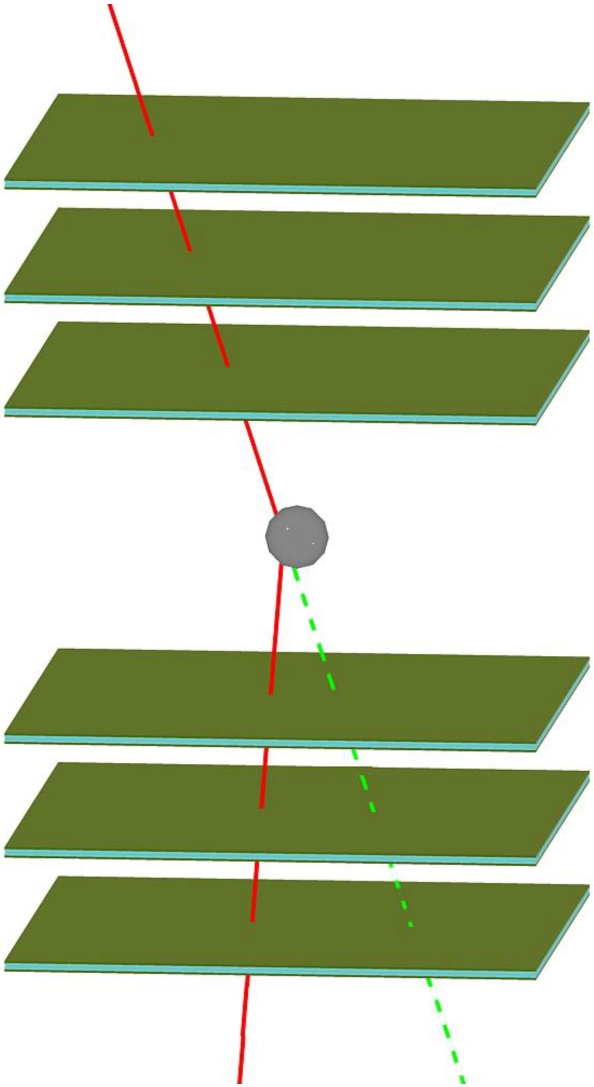
Outlook

- Introduction
  - Motivation
  - Muon scattering tomography
  - Detector requirements
- Setup overview
  - RPC
  - Electronics
  - Hardware
- Data
  - Analysis overview
  - Summary of read-out performance
- Current developments
- Summary



Motivation

- University of Bristol (UoB) and Atomic Weapon Establishment (AWE) partnership.
- Develop, build and study a prototype scanner for Muon Scattering Tomography (MST).
- Scan a target volume in search of special nuclear materials (SNM).

Why?

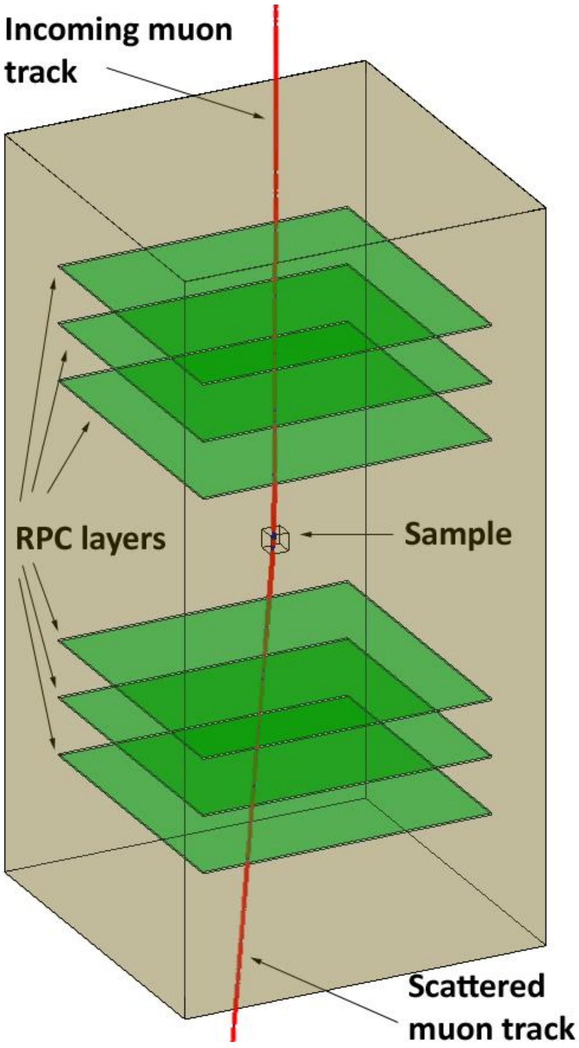
- National nuclear security is a hot topic
- Illicit movements of SNC needs to be prevented and detected.
- Every year 7.5M shipping containers cross the UK borders.
- Scanning cannot hinder shipping operations (~1 minute per container)

Motivation

Why muons?

Cosmic muons are excellent probes:

- Readily available, with flux of ~100 Hz/m^2
- Virtually impossible to screen against.
  - For 1 GeV muons dE/dx ~ 2 MeV•g^{-1}•cm^2.
- Charged; can be easily detected.
- No radiation hazard for the scanner operators.
- No radiation hazard for the cargo content.
  - Food
  - Electronics
  - Living beings

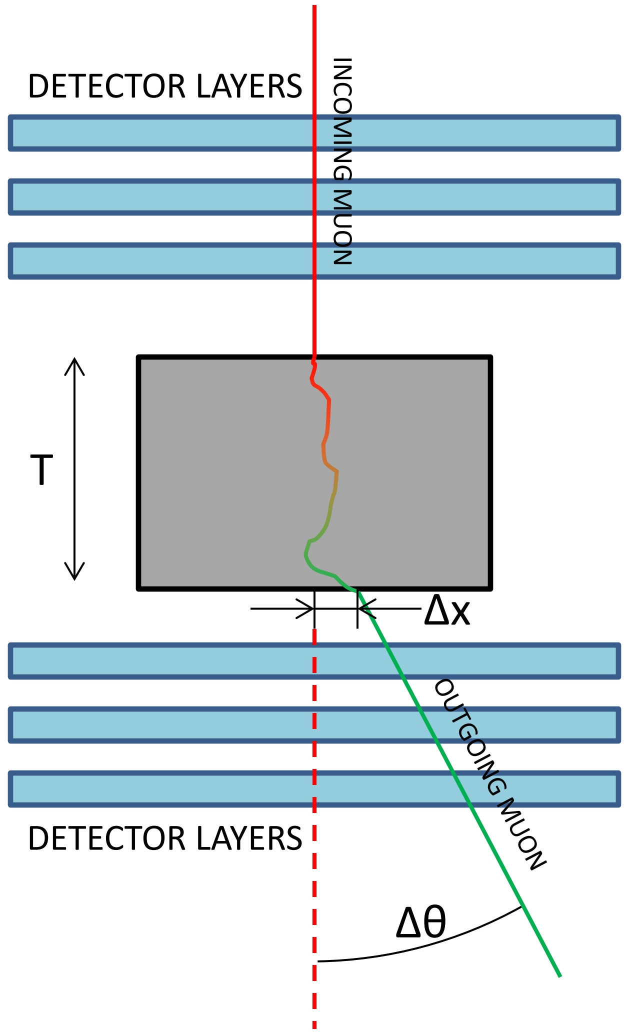


Muon scattering tomography

- Muons undergo multiple coulomb scattering within the detector volume.
- The angular distribution can be assumed to be Gaussian, with σ^2_0 depending on the radiation length X_0 (and ultimately on ρZ^2).
- Muon tracks scattering within the target volume provide information of its content.
- High sensitivity to high-Z, high-density materials.

$$\sigma_0^2 \approx \left(\frac{15MeV}{pc\beta}\right)^2 \frac{\mathrm{T}}{\mathrm{X}_0}$$

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

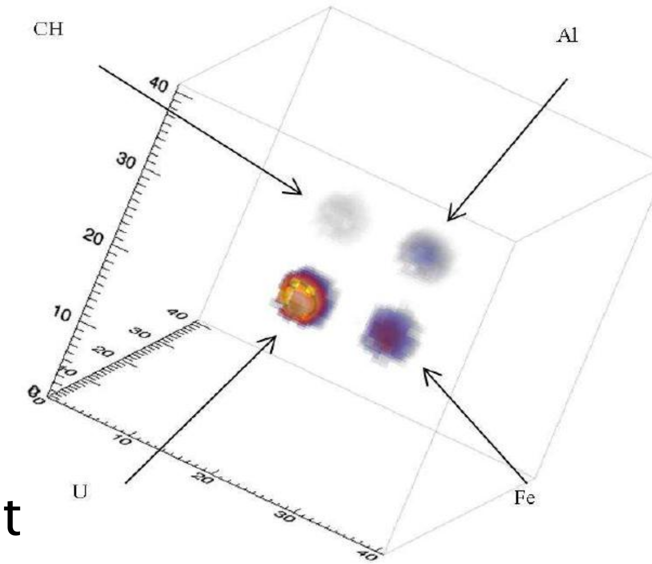


Detector requirements

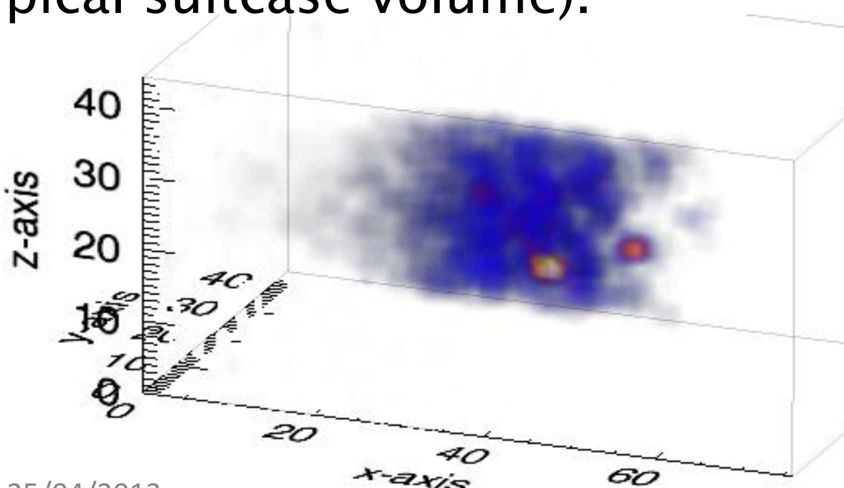
AWE simulations provide guidelines for the detectors:

- Angular resolution: ~ 10 mrad
- Spatial resolution of ~800 μm in our setup
- Time resolution: ~ ns
- Efficiency: above 90 %

With these features it is possible to reconstruct a tennis ball sized object within 30 seconds (in a typical suitcase volume).



Reconstructed image showing muon scattering from tennis ball of different materials in a typical suitcase volume (courtesy AWE).



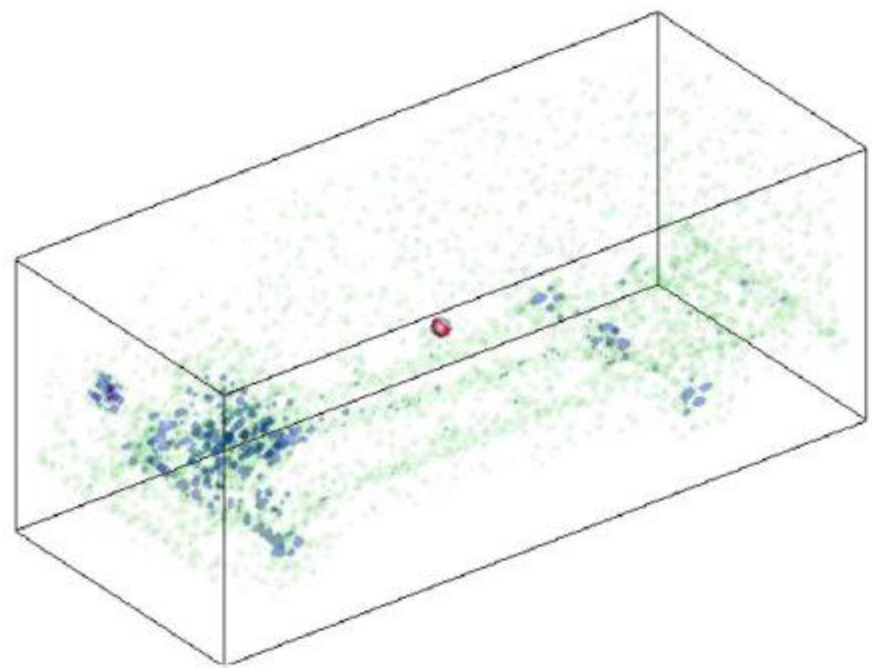
Reconstructed image of a waste drum filled with concrete and containing cubes of iron, lead, uranium and air. The cubes made of U and Pb are easily identified (courtesy AWE).

Detector requirements

Practical use of MST introduces some additional requirements:

- Large area (shipping containers, trucks)
- Scalability
- Low cost per unit area
- Robustness

Resistive Plate Chamber are a very good option for MST



Top:
Simulation of a passenger van containing a tungsten block (10 cm x 10 cm x 10 cm).
Bottom:
Reconstruction of 1 minute of simulated muon exposure for the van above. The tungsten block is clearly visible.
(source: Schultz et al., *"Statistical Reconstruction for Cosmic Ray Muon Tomography",* IEEE TRANSACTIONS ON IMAGE PROCESSING, VOL. 16, NO. 8, AUGUST 2007)

Detector requirements

2005 International Linear Collider Workshop - Stanford, U.S.A.

Digital Hadron Calorimetry with Glass RPC Active Detectors

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Glass RPC detectors are an attractive candidate for the active part of a highly granular digital hadron calorimeter (DHCAL) at the ILC. A numerical study, based on the GEANT3 simulation package, of the performance of such a calorimeter is presented in this work. A simplified model for the RPC response, tuned on real data, is implemented in the simulation. The reliability of the simulation is demonstrated by comparison to existing data collected with a large volume calorimeter prototype exposed to a pion beam in an energy range from 2 GeV to 10 GeV. In view of an optimization of the readout pitch, a detailed study of the energy and position resolution at the single hadron level for different read-out pad dimensions is presented. These results are then used in a parametric form to obtain a preliminary estimate of the contribution of DHCAL to the reconstruction of the energy flow at the ILC detector.

2007 IEEE Nuclear Science Symposium Conference Record N29-3

HARDROC1, Readout chip of the Digital Hadronic Calorimeter of ILC

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It seems that, after all, we have something in common.

Resistive Plate Chambers for hadron calorimetry: Tests with analog readout

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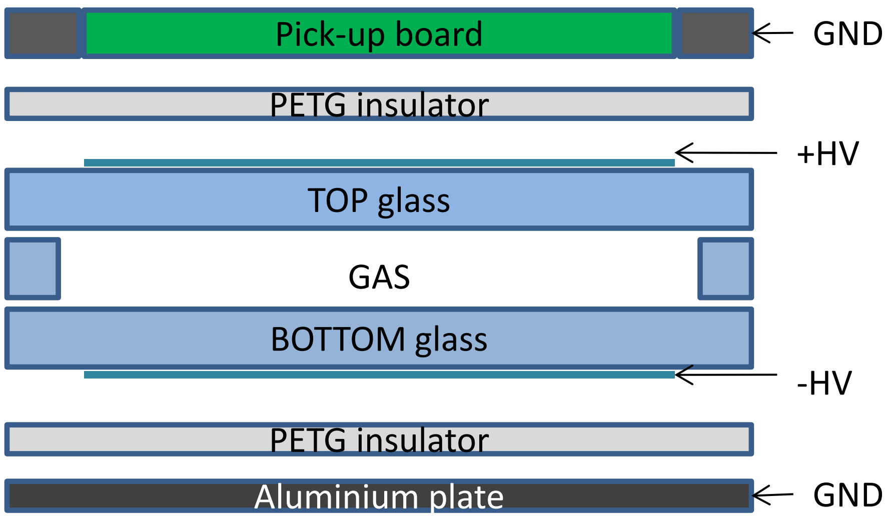
Abstract

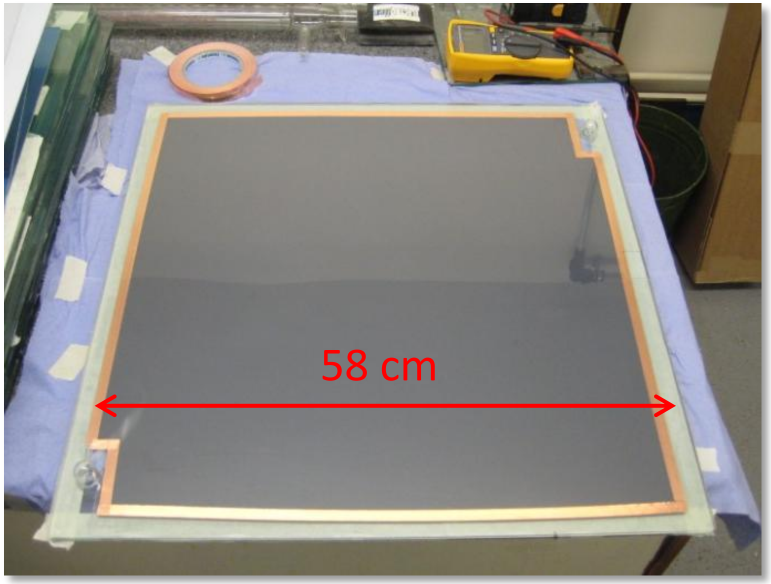
Resistive Plate Chambers (RPCs) are being developed for use in a hadron calorimeter with very fine segmentation of the readout. The design of the chambers and various tests with cosmic rays are described. This paper reports on the measurements with multi-bit (or analog) readout of either a single larger or multiple smaller readout pads.

PACS: 29.40.Vj; 29.40.Cs; 29.40.Mc; 29.40.Wk

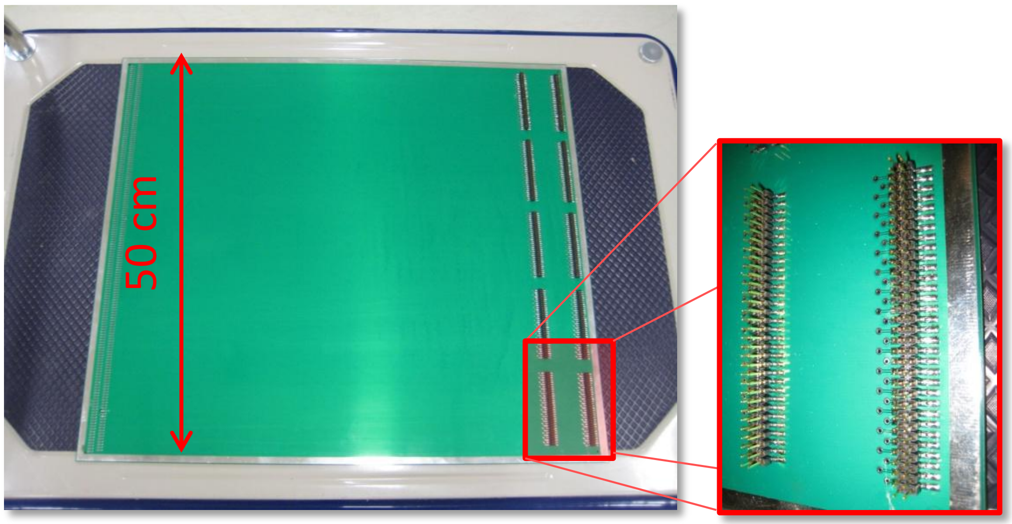
Keywords: Calorimetry; Linear collider; Particle Flow Algorithms; Resistive Plate Chambers

Setup – RPC



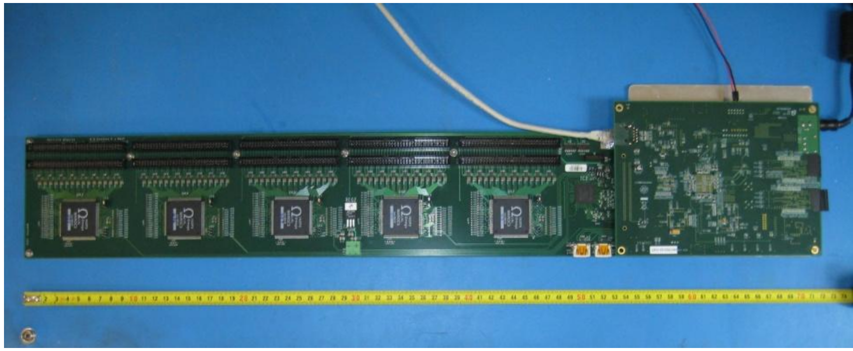


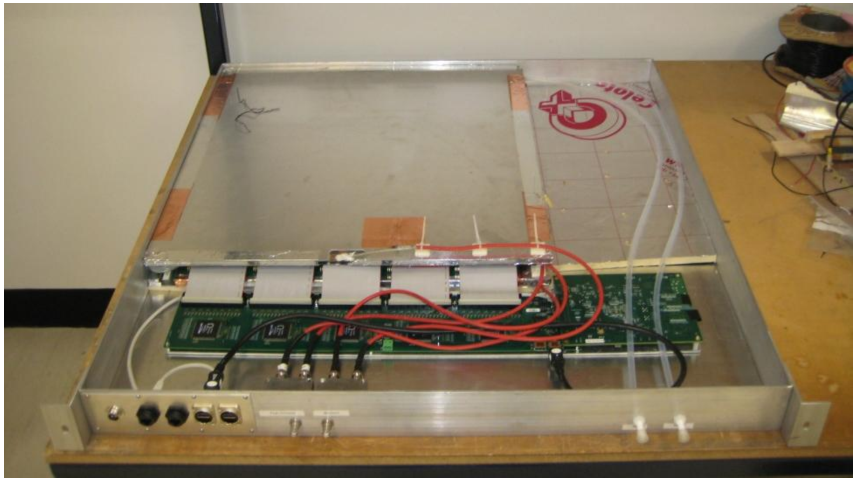
- Glass RPC
- 2 mm gas gap
- Freon, iso-butane (95%, 5%)
- 50 cm x 50 cm active area
- Resistive coating (500 kΩ/□)
- 320 strips per RPC provide 1D readout
- Strip pitch: 1.5 mm
- Strip length: 50 cm



Setup – Electronics

- Front-end: MAROC chips
  - 64 analog inputs
  - Built-in analog-to-digital converters (ADC)
  - 12 bits
  - 32.5 MHz clock
  - Self trigger capability
- Readout board
  - 5 MAROCs
  - Programmable logic interface (FPGA)
  - Communication via Ethernet bus (IP-bus)
- The 320 strips from an RPC are fed to one readout board.
- 2 RPCs are hosted in cassettes with the readout.





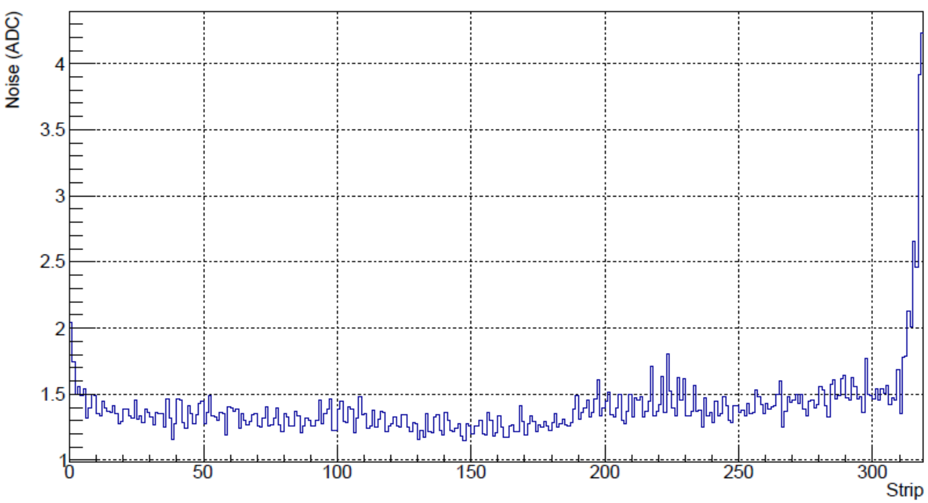
Setup – Hardware overview

- 6 readout planes (cassettes)
- Each cassette provides a 3D point for the muon track
  - 2 glass RPC per cassette (X,Y)
  - Front-end electronics
  - Gas and high voltage connectors
  - Easy to swap/change configuration
- The cabinet includes the gas mixing rig and HV system.

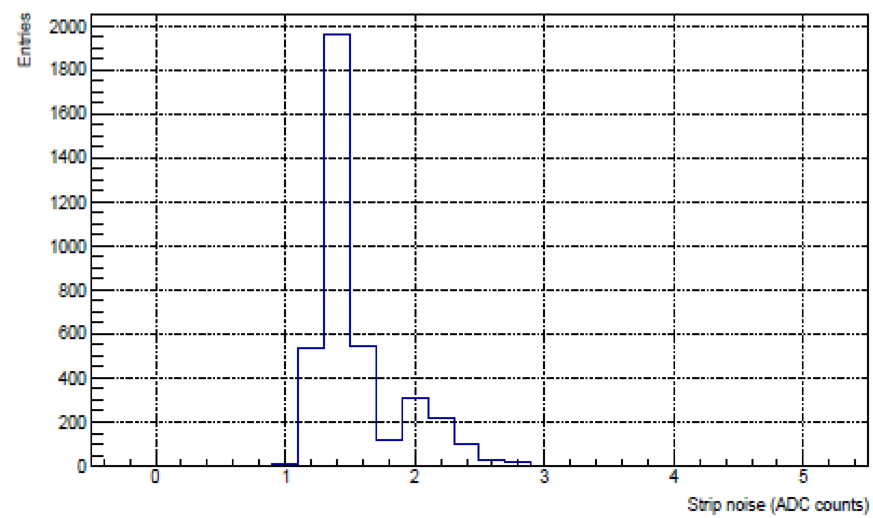
Data analysis

- All data presented is taken with external trigger
- Data saved to disk and processed offline
- Pedestal run to estimate noise on each strip

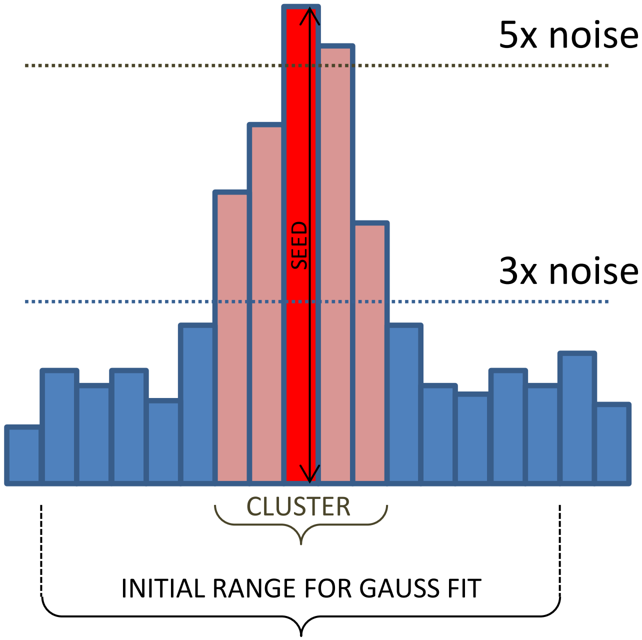
Noise per strip on one RPC

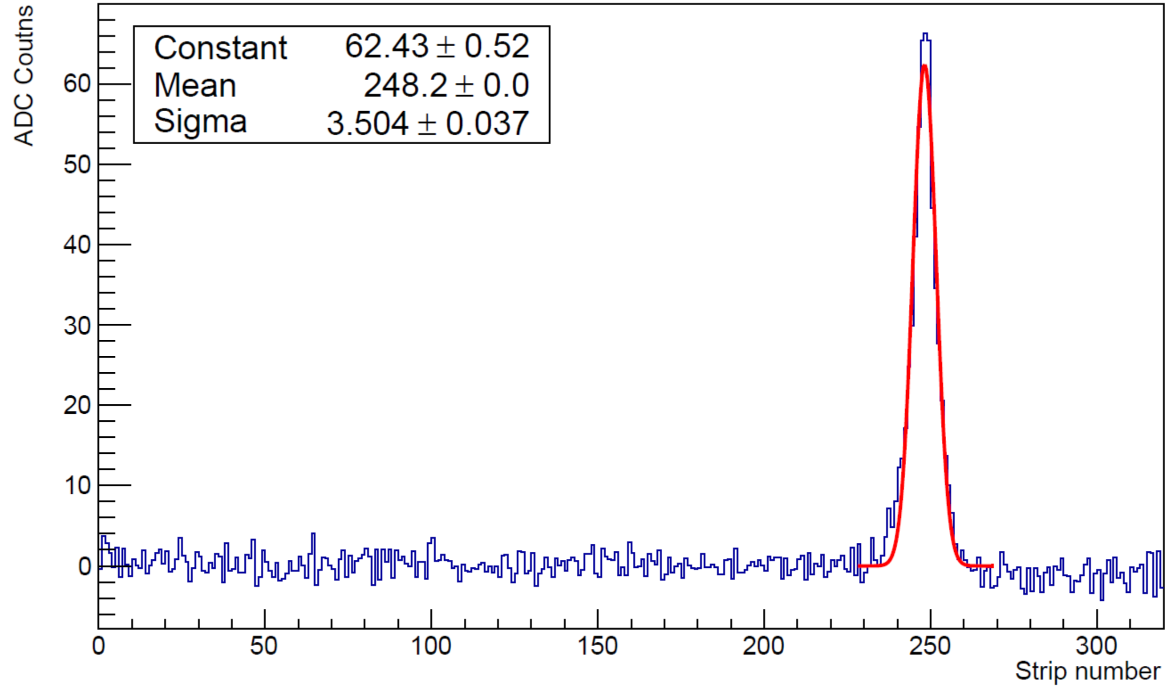


Noise distribution across all the strips



Signal

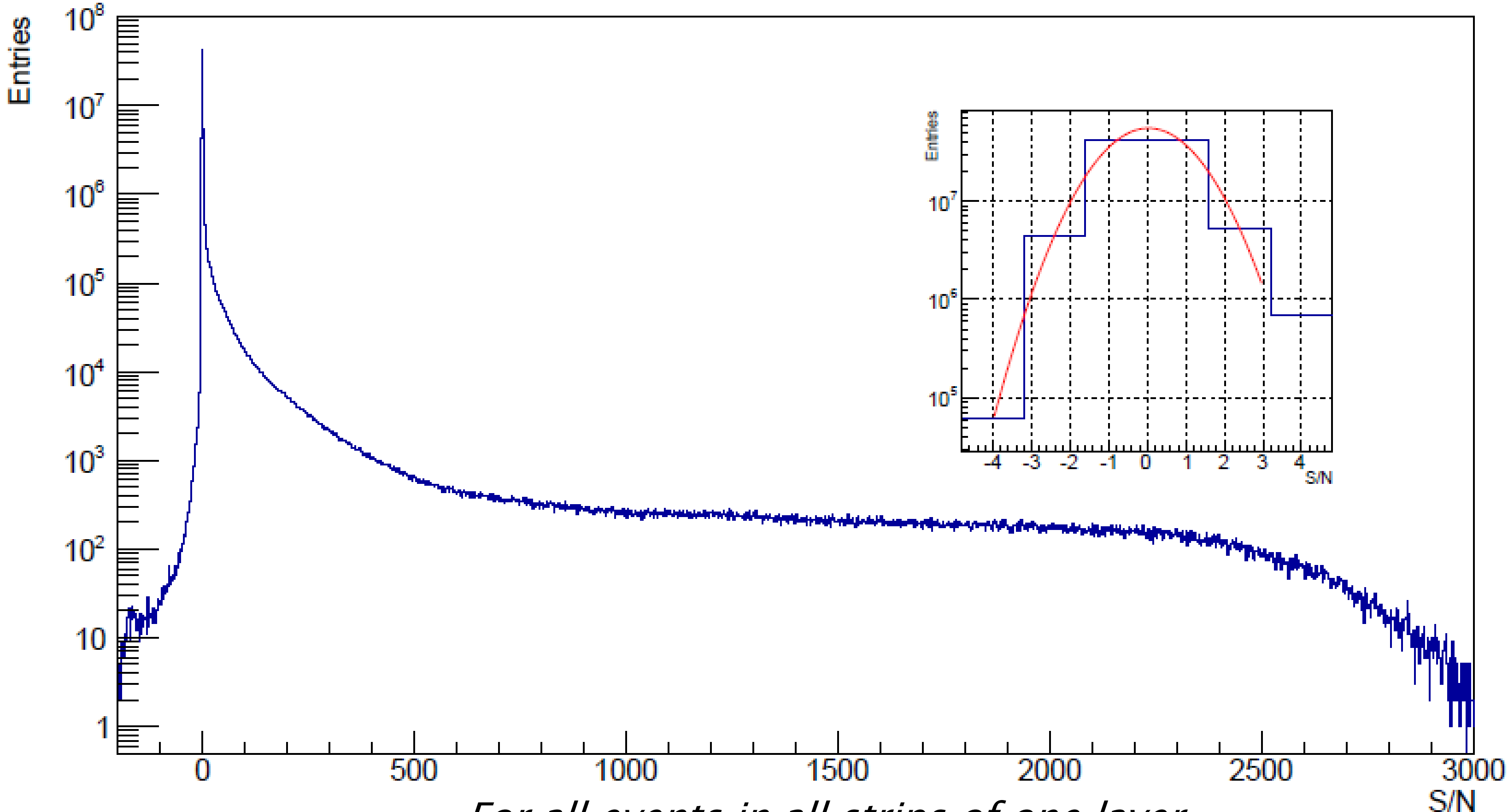




Typical signal after pedestal subtraction and common mode correction.
Hit finding requirement based on signal-to-noise value (S/N):

- -SEED (peak) S/N ≥ 5
- -CLUSTER S/N ≥ 3
- -Gauss fit around cluster+5 strips

Signal to noise distribution



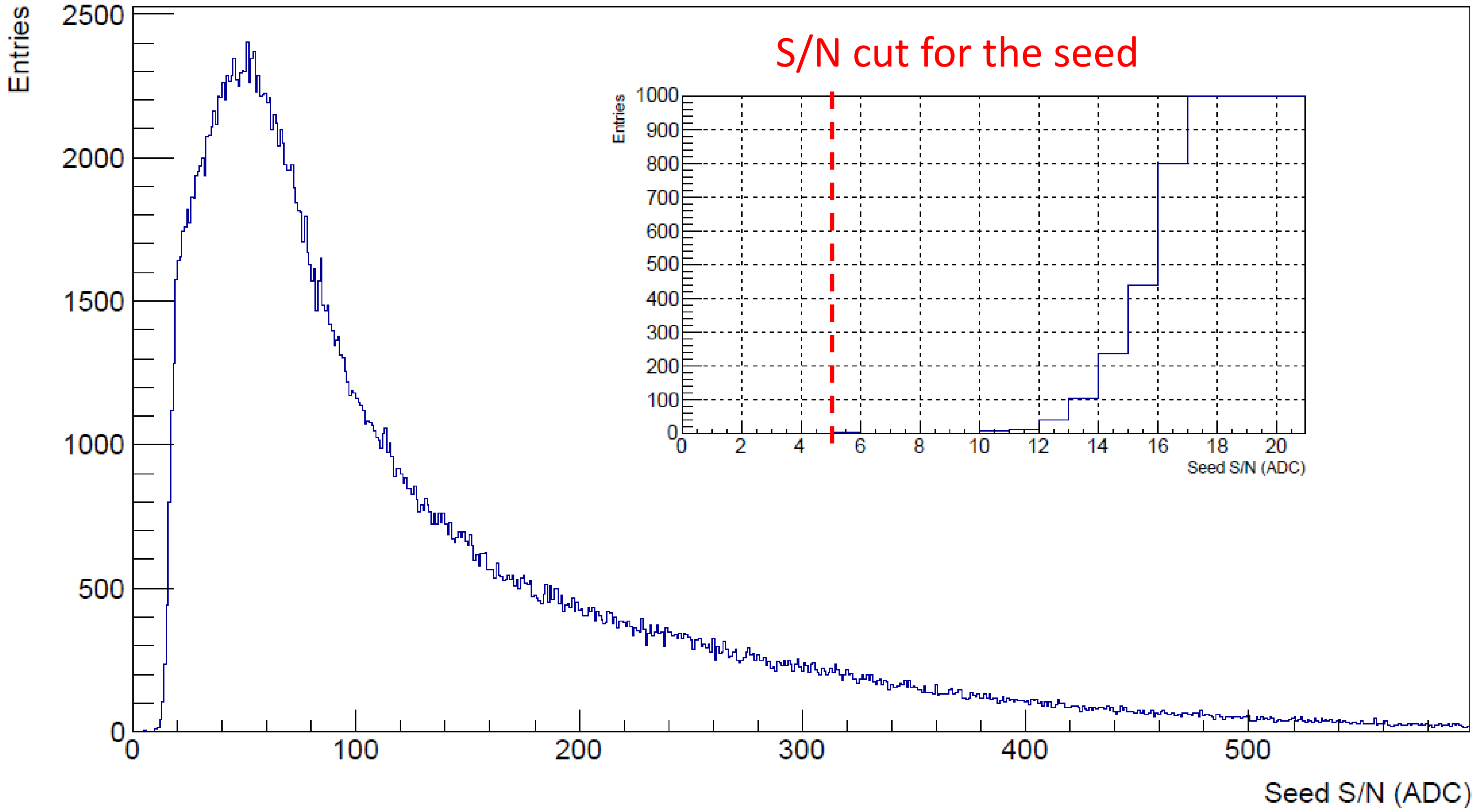
For all events in all strips of one layer.

Noise is properly estimated in all the layers:

-fit centred around 0 (max. $\Delta = 0.04$)

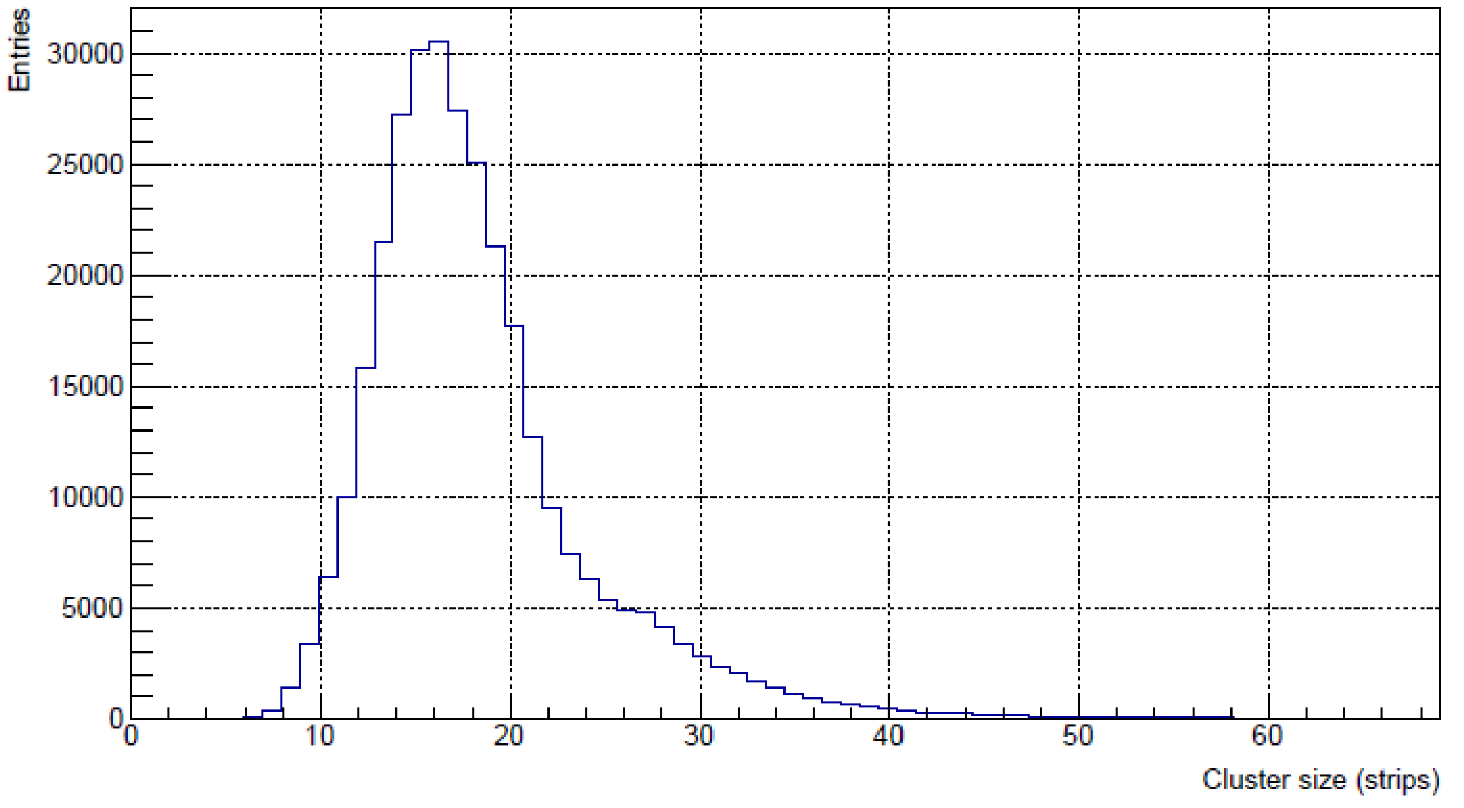
-$0.992 < \sigma < 1.045$

Seed S/N distribution



The S/N>5 cut does not affect the detector efficiency.

Cluster size



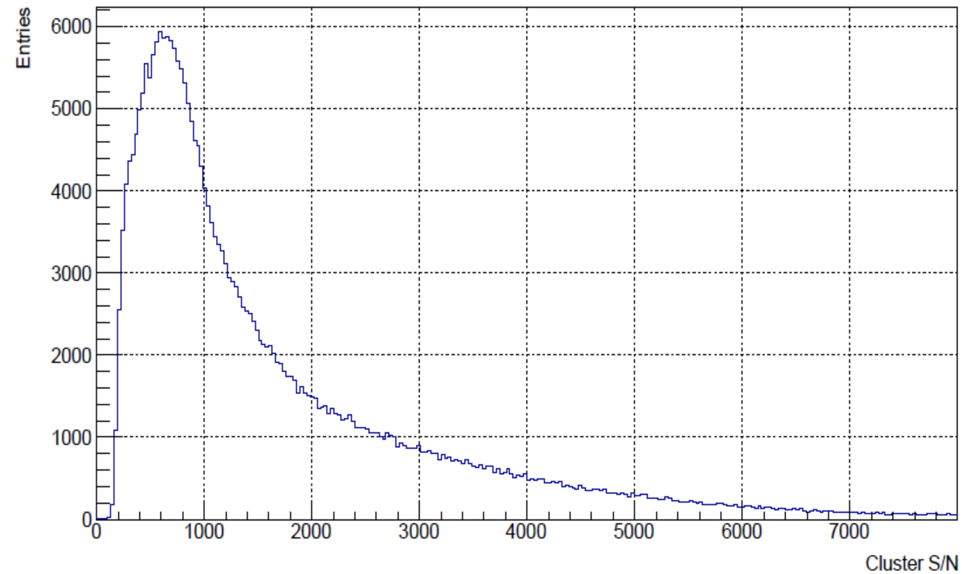
The cluster size distribution shows that we could increase the strip pitch without degrading hit reconstruction quality.

Detectors signal performances

All layers have very good S/N values, both in terms of seed and cluster.

Differences due to the HV system and variations in the RPC assembly.

A few layers show signs of streamers. This affects their performances:
-clusters too big
-saturated strips

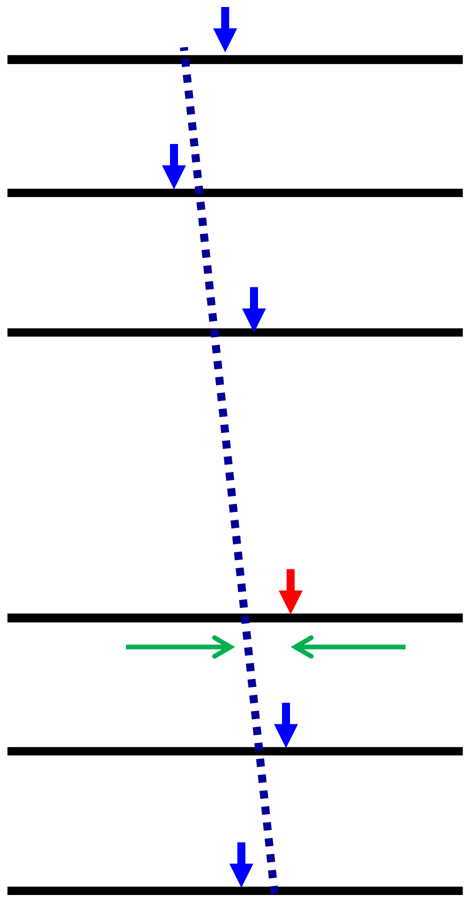


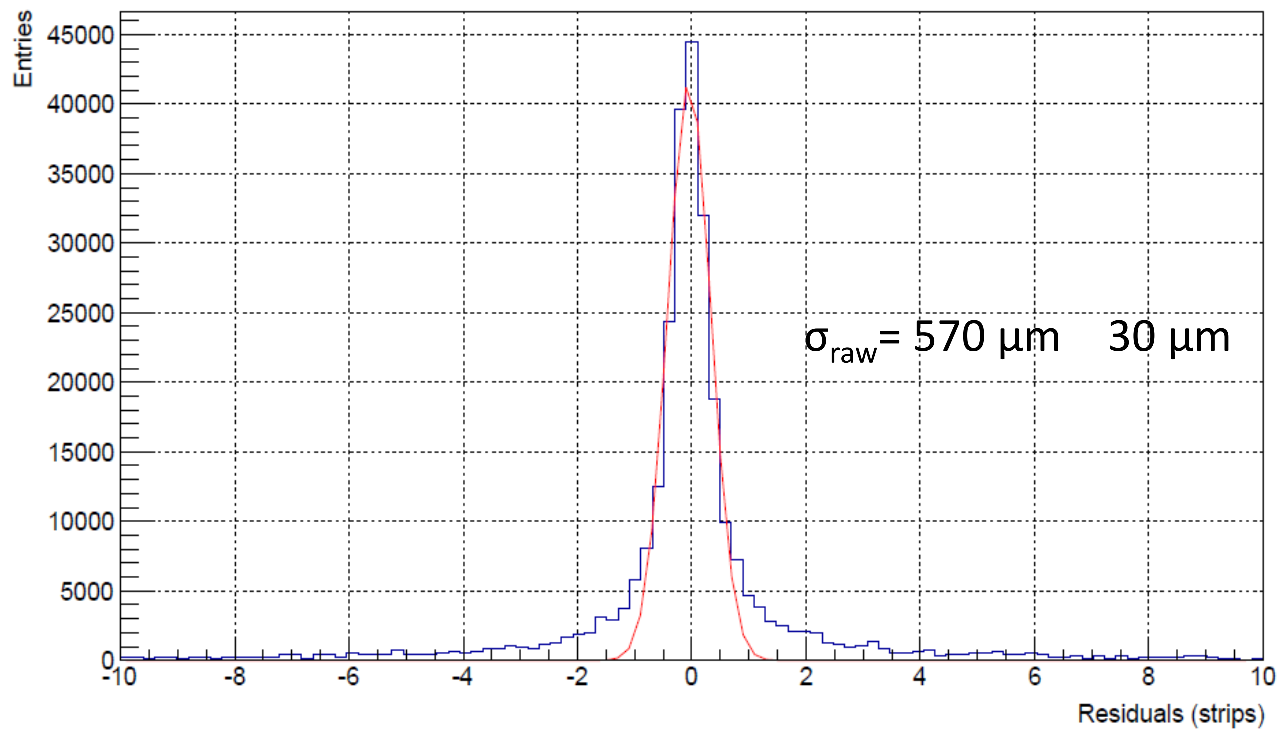
Layer	Noise (ADC)	Seed (ADC)	Seed S/N	Cluster (ADC)	S/N
0	2.17 ± 0.27	31.2 ± 0.5	15.2 ± 0.4	490 ± 30	226 ± 31
1	1.59 ± 0.34	54.2 ± 0.3	30.8 ± 0.2	635 ± 10	399 ± 86
2	1.40 ± 0.14	88.5 ± 0.1	63.7 ± 0.3	908 ± 20	649 ± 66
3	1.39 ± 0.28	68.4 ± 0.1	49.6 ± 0.2	817 ± 20	588 ± 119
4	1.40 ± 0.18	57.9 ± 0.1	42.1 ± 0.5	769 ± 5	549 ± 71
5	1.40 ± 0.19	46.2 ± 0.2	38.2 ± 0.2	597 ± 10	426 ± 58
6	1.36 ± 0.13	58.4 ± 0.1	28.7 ± 0.2	1418 ± 30	1043 ± 102
7	1.41 ± 0.19	58.3 ± 0.1	37.1 ± 0.3	891 ± 5	632 ± 85
8	1.53 ± 0.27	42.3 ± 0.1	30.1 ± 0.4	773 ± 20	505 ± 90
9	2.07 ± 0.25	27.6 ± 0.5	13.3 ± 0.8	442 ± 20	214 ± 28
10	1.45 ± 0.16	31.7 ± 0.8	22.0 ± 0.9	330 ± 60	228 ± 48
11	1.35 ± 0.11	29.8 ± 0.1	24.1 ± 0.5	510 ± 10	378 ± 32

Table summarizing the average noise per layer and the most probable value of the Seed, Seed S/N, Cluster integral and S/N distributions.

Track residuals

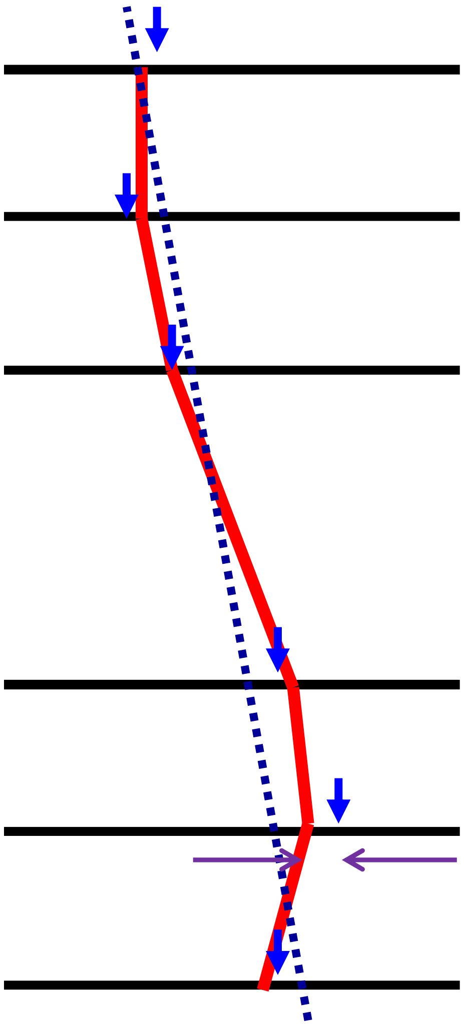
- Reconstruct hit positions in each layer
- Straight line removing layer under test (LUT)
- Compare reconstructed position in LUT with hit extrapolated position
- Residual distribution yields raw resolution





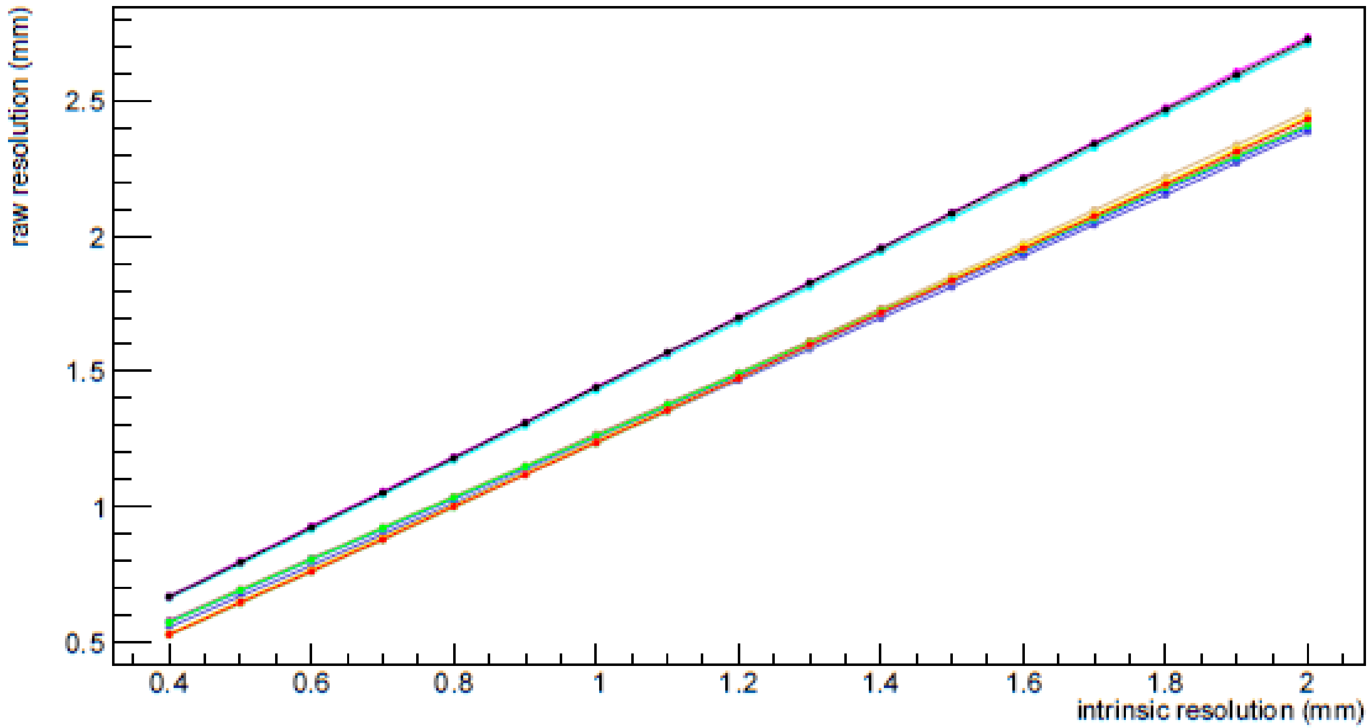
Track residuals

- Raw resolution is not a good parameter for detector performance
  - includes multiple scattering and extrapolation errors
- Need to measure the intrinsic resolution (distance arrow from red line and not arrow from dashed line).
- Done in large MC study

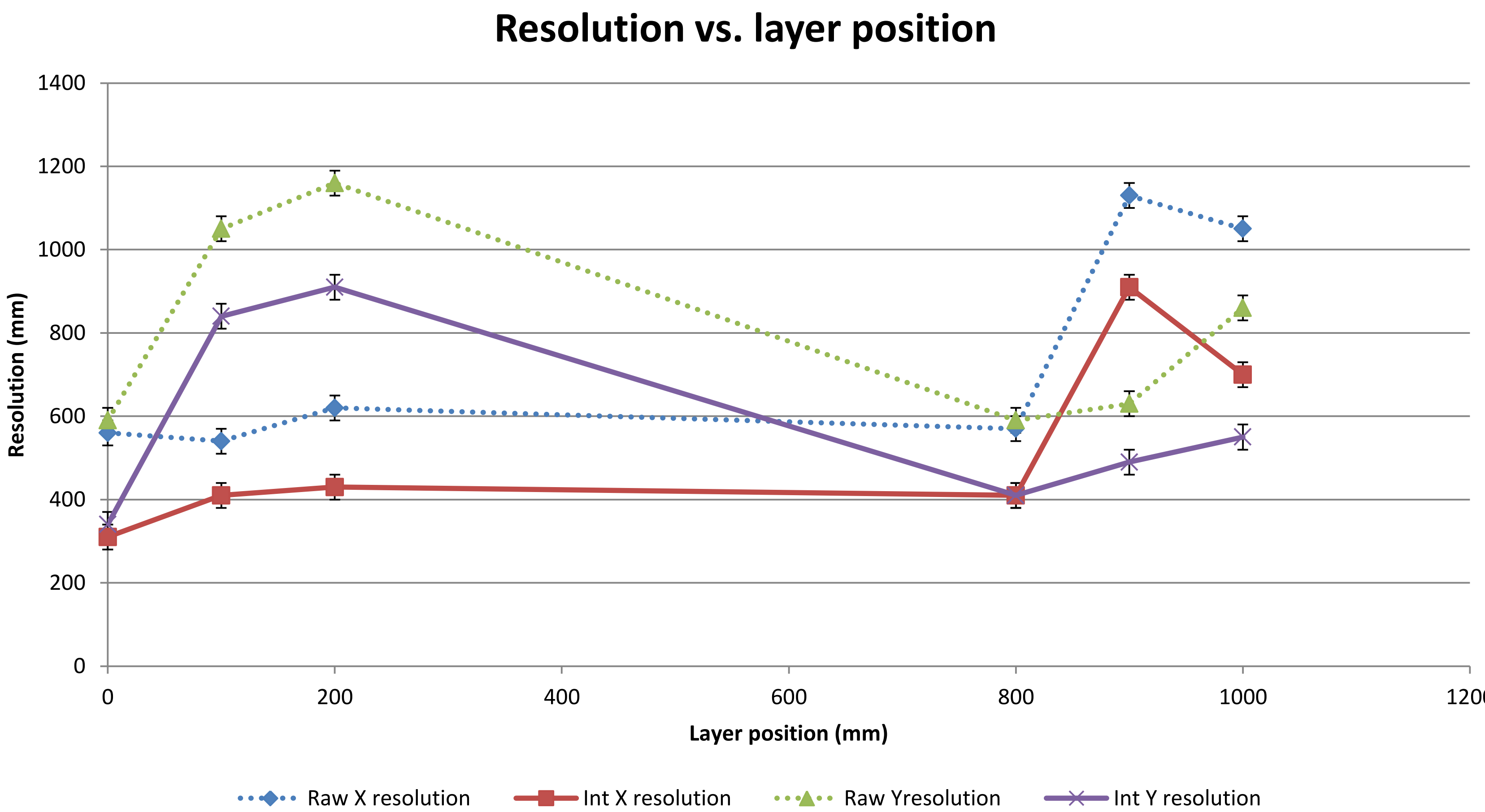


Intrinsic resolution

- Simulated entire set up in Geant4.
- Know material in set up. Know momentum spectrum muons.
- Apply an intrinsic resolution and see what the raw resolution is.



Intrinsic resolution



Intrinsic resolution between 300 μm and 900 μm.
Still tweaking the system and the analysis to improve results.

Efficiency and purity

- Efficiency: probability of seeing a hit when a muon traverses the layer.
- Purity: probability that when a hit is seen, it is actually due to a crossing muon (and not to noise or sparks in the RPC).

- In our analysis we can currently only estimate a lower limit for purity.

- Overall, most layers perform well:
  - Efficiency above 94%
  - Purity above 95%
- Still some work to be done.

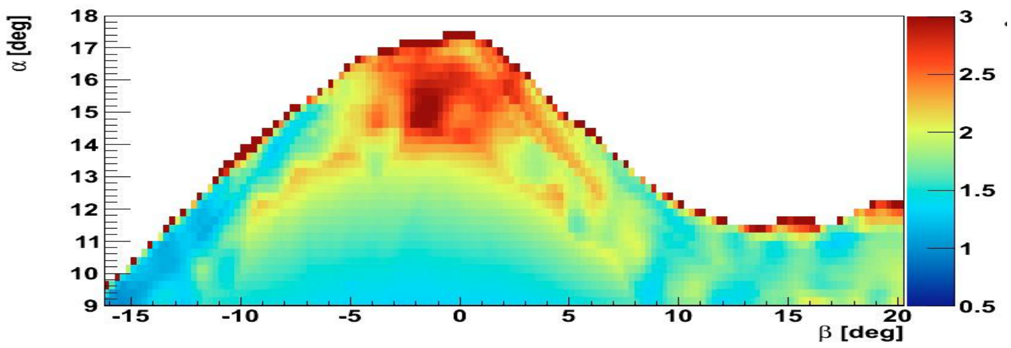
Layer	Efficiency %	Purity %
0	97.3 ± 0.4	97.97 ± 0.03
1	96.5 ± 0.4	94.05 ± 0.07
2	94.3 ± 0.5	94.97 ± 0.05
3	98.3 ± 0.3	95.91 ± 0.04
4	96.8 ± 0.3	96.75 ± 0.03
5	97.0 ± 0.3	94.59 ± 0.04
6	99.2 ± 0.2	97.27 ± 0.02
7	97.5 ± 0.4	95.54 ± 0.04
8	91.9 ± 0.6	95.58 ± 0.04
9	89.9 ± 0.8	92.89 ± 0.02
10	85.8 ± 0.9	96.22 ± 0.02
11	95.6 ± 0.5	95.77 ± 0.03

Current developments

- Replace HV system to drive RPC individually.
- Improve analysis
- Cost of full system depends mainly on how much area can be covered by 1 strip:
  - Study how strip length affects performances. Can we have 2 m long strips?
  - Study how strip pitch affects performances. Can we use less readout channels?
- We are building 600 mm X 1800 mm RPCs to be used in a full size scanner at AWE.

Other applications

- Volcano monitoring



C. Carloganu, LPC clermont Ferrand IN2P3/CNRS

- Nuclear waste monitoring
- Lots of drums with nuclear waste with "unknown" contents
- Need to build up 3D density profile with proper tomography

Conclusions

- We successfully built an tested a prototype to track muons with fine pitch RPC.
- The prototype is suitable to perform Muon Scanner Tomography:
  - The system behaves well. Efficiency better than 95% in most layers. Purity better than 94%.
  - Sub-millimeter spatial resolution; sufficient to detect high-Z materials.
  - Resolution can be further improved by tuning the analysis and the system.
- We are currently embarking on additional studies:
  - Maximum strip length.
  - Optimal strip pitch.
  - Making the system portable.
- We look forward to further developing this project into a full scale container scanning system in collaboration with our industrial partner AWE.
- We plan to use our detectors for volcano monitoring, in conjunction with the TOMUVOL collaboration.
- We also plan to apply the muon tomography to nuclear waste monitoring.

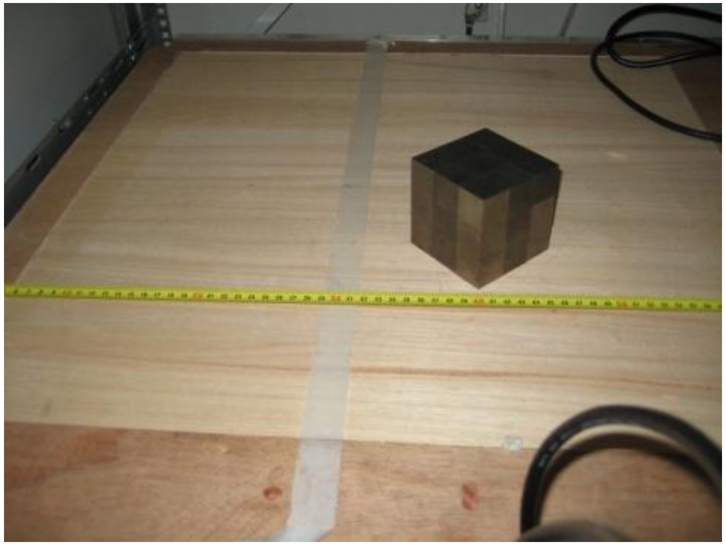
End

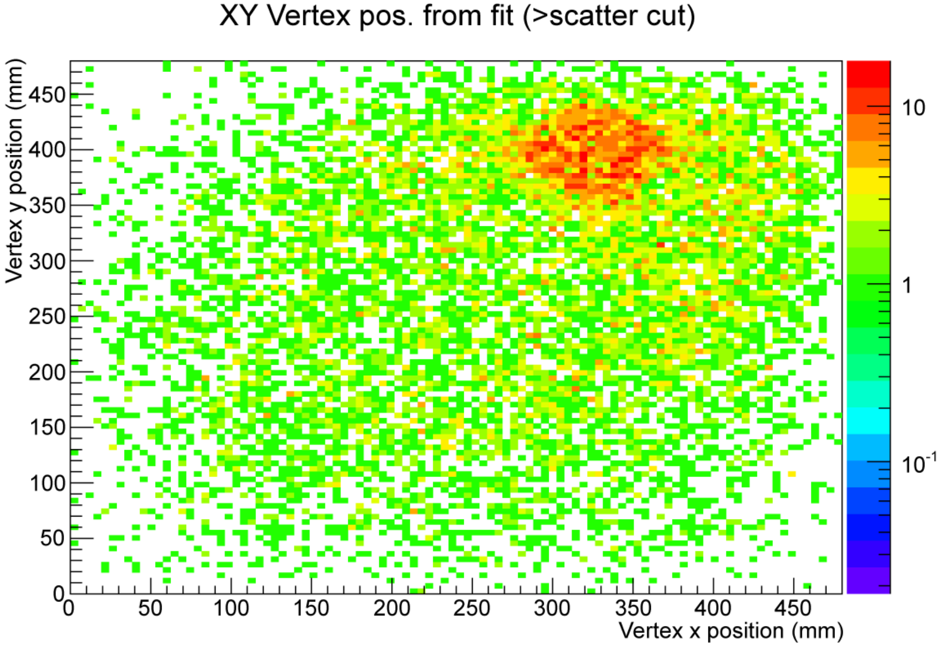
Spare slides

Abstract

Following their introduction in the physics community in the early ’80s the use of Resistive Plate Chambers (RPCs) as charged particles detectors has constantly increased. Low cost per unit area, good time resolution and easy of operation are some of the features that contributed to such large adoption and that make RPCs interesting for several applications. We built a prototype detector to track cosmic muons and exploit the information provided by estimating the multiple coulomb scattering angle to determine the type of materials they traversed.
Very high efficiencies and purities and a position resolution better than 0.5 mm have been obtained. We will present these results and report on the detection of high-Z materials. We will also outline our plans to further improve our detectors with the aim of their application in volcano topography and as active material in calorimeters.

AWE blocks





7.5 cm x 7.5 cm x 7.5 cm of tungsten, imaged with the MAROC system.
No momentum information.
Very crude analysis.

VERY PRELIMINARY