A Digital Calorimeter For The Muon Collider

Yasar Onel

University of Iowa

Why Digital Calorimetry?

- Idea emerged from the need of high segmentation calorimetry for the application of Particle Flow Algorithms[1] (PFAs). An analog readout solution would result in unrealistic data sizes.

- Simple digital readout with a threshold set well below the signal given by one minimum ionizing particle traversing the active medium.

- Comparable resolution with the analog readout.[2]

- A perfect calorimetry solution for the muon collider providing high segmentation in a robust and sophisticated approach.

[1] Session on PFAs in XII International Conference on Calorimetry in High Energy Physics, Chicago, AIP Conf. Proc. 867 (2006) N. Graf et al., 523; L. Xia, 531; P. Krstonosic, 538; D. Chakraborty et al., 546.

[2] J. Repond, NIM A 572 (2007) 211–214; J. Repond, NIM A 518 (2004) 54–58.

Digital Calorimetry For Muon Collider

For a Muon Collider detector, the key points are the identification and measurement of W, Z and Higgs bosons and heavy quarks and leptons, and the ability to distinguish between them. This wide spectrum of measurement-ready physics could also get extended by several orders depending on the results of the LHC (discovery of new physics like SUSY, extra dimensions, etc.). In the event of this particle/phase-space extension, the challenge for the detectors increases even further.

The solution, indeed, requires increased segmentation in calorimeters. This high segmentation requirement can only be achieved with digital readout.

A digital calorimetry with Resistive Plate Chambers (RPCs) provides the necessary transverse segmentation, robustness, detection efficiency, readout integrity and radiation hardness demanded by a Muon Collider. Apart from the readout concept, a digital calorimeter with RPCs offers negligible noise and background interference and well-identified environmental dependence. A high granularity calorimeter system (both electromagnetic and hadron calorimeters) with an efficient tracker will be the future of particle detectors and the only feasible solution for this kind of a detector approach is a calorimeter system with digital readout.

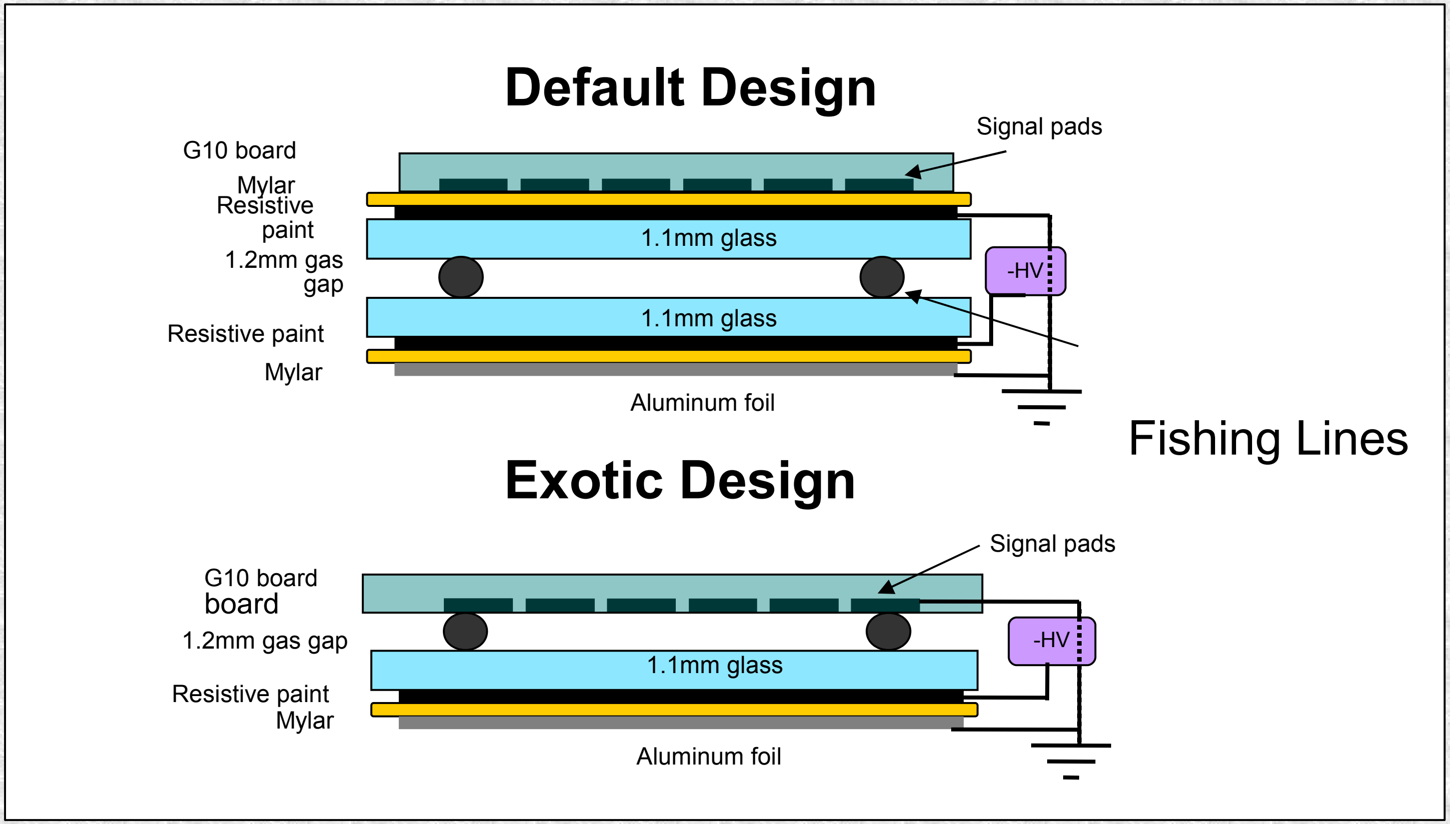
A Digital Hadron Calorimeter With RPCs

This talk will

- Report on the development of a finely granulated Digital Hadron Calorimeter (DHCAL) using Resistive Plate Chambers (RPCs) as the active medium,

- Describe calibration and various measurements performed with a stack of nine chambers exposed to the muons, protons, pions and positrons of the Fermilab test beam.

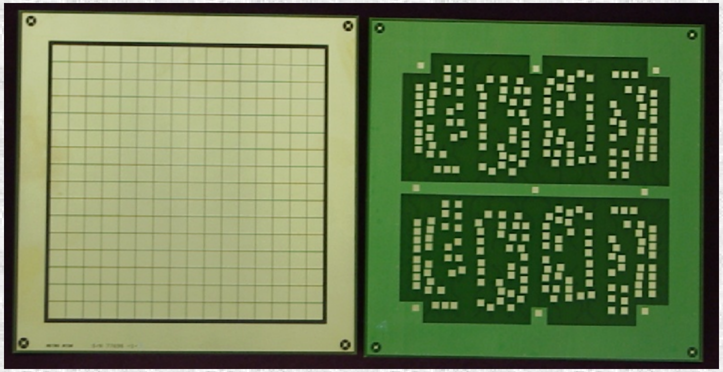
Description of the Calorimeter Stack



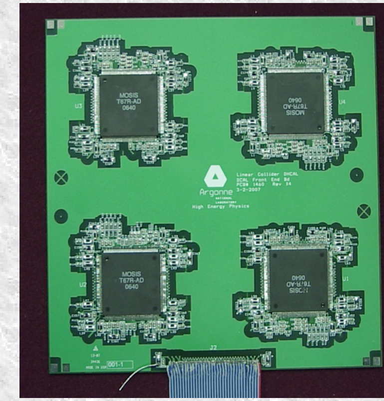
The calorimeter stack consisted of nine chambers interleaved with the combination of a steel (16 mm) and a copper (4 mm) absorber plates, corresponding to approximately 1.2 radiation length. Not all layers were used for all measurements.

The chambers measured 20 x 20 cm^2. They were operated in avalanche mode with an average high voltage setting around 6.1 kV. The gas consisted of a mixture of three components: R134A (94.5%), isobutane (5.0%) and sulfur-hexafluoride (0.5%).

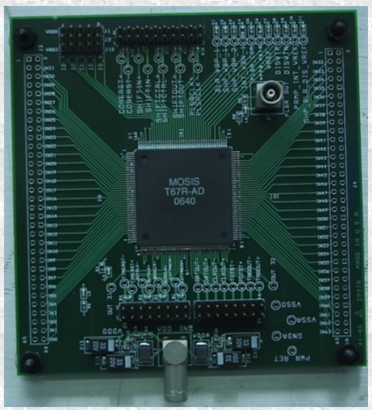
Electronic Readout System



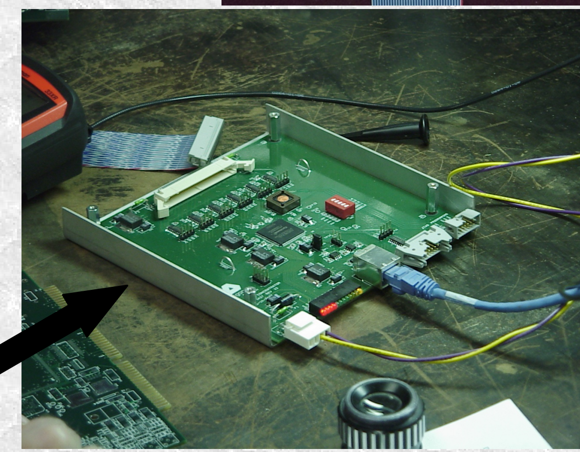
Pad Board



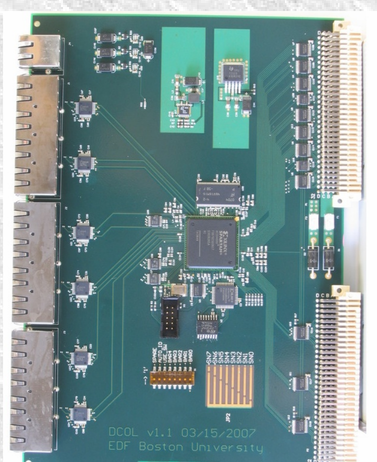
Front-End Board



DCAL Chip

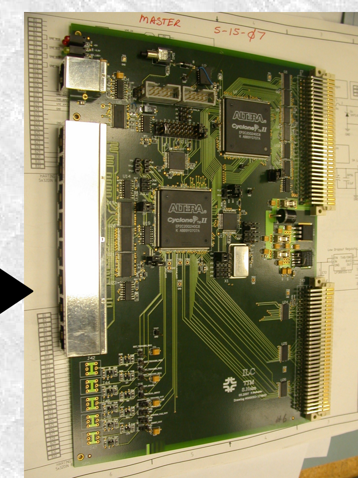


Data Concentrator



Data Collector

Trigger and Timing Module



The total number of readout channels was up to 2,304 for nine layers.

Calibration Procedure

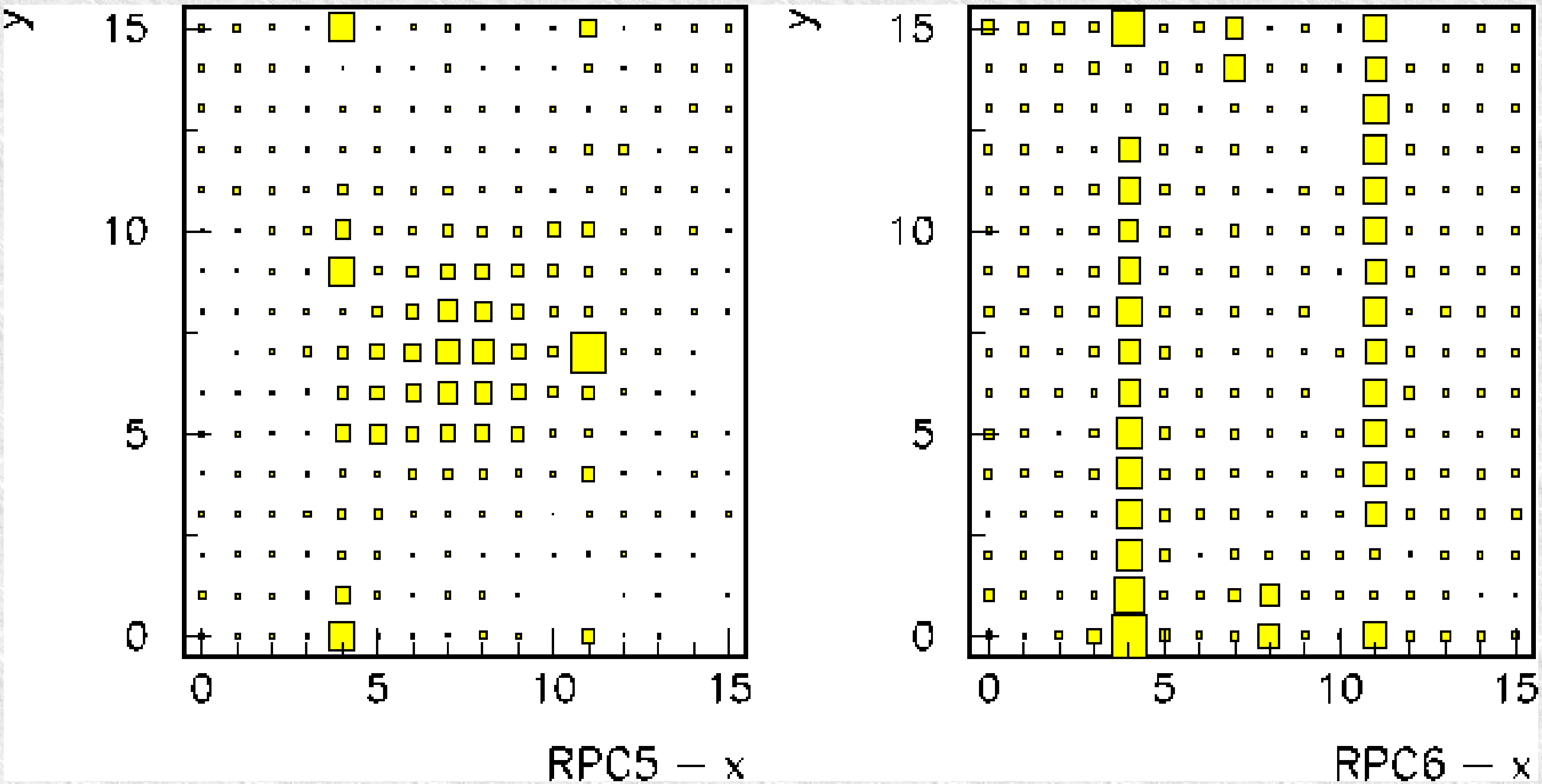
$E_{hadron} = \alpha_{samp}(\Sigma_i H_i) \cdot \Sigma_i(H_i\text{-}B_i)/((\varepsilon_i^{MIP}/\varepsilon_0^{MIP})\cdot(\mu_i^{MIP}/\mu_0^{MIP}))$

where,

- i is an index running over all pads associated with an incoming particle
- H_i is set to 1 (0) depending on whether a hit (or no hit) has been recorded in pad i
- B_i are the expected number of background hits (from accidental discharges, electronic noise or cosmic rays)
- ε_i^{MIP} is the efficiency for pad i to fire when traversed by a minimum ionizing particle (MIP)
  $\varepsilon_i = N_i^{hits}{>}0 / N_i^{total}$ (binomial errors are calculated for efficiency)
- μ_i^{MIP} is the average number of pads firing when pad i is traversed by a MIP, where the 'zeros' are excluded from the average (standard errors are calculated for pad multiplicity) and $\alpha_{samp}(\Sigma_i H_i)$ is a sampling term, possibly depending on the total number of hits.

ε_0^{MIP} and μ_0^{MIP} are the average efficiency and the pad multiplicity of the stack.

Measurement of the Noise Rate

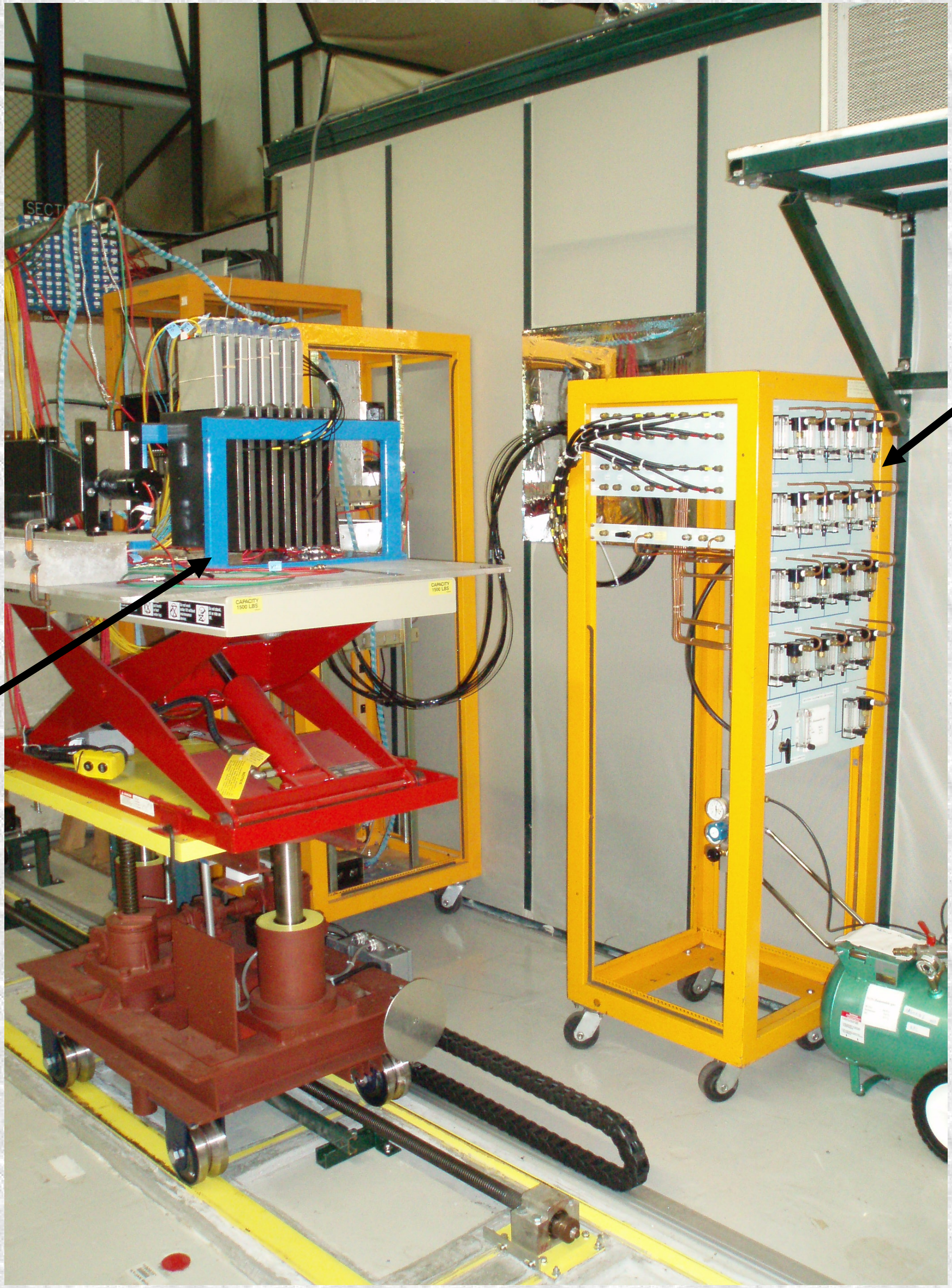


x – y map of the noise hits for a typical default (RPC5) and the ‘exotic’ (RPC6) chamber. A clear clustering along the fishing lines located approximately at x = 4.2 and 10.7 is visible.

The noise rate at our default threshold setting of 110 DAC counts corresponds to about 0.15 Hz/cm^2. Extrapolated to a calorimeter with say $50 \cdot 10^6$ channels, this rate in turn corresponds to 0.2 hits/event.

Test Beam Setup and Data Collection

The gas distribution rack



The stack containing nine layers within the blue hanging file structure

Analysis Procedures

Different analysis procedures were applied for

- calibration with muons[1],
- positron[2] and pion[3] shower measurements and
- rate measurements[4].

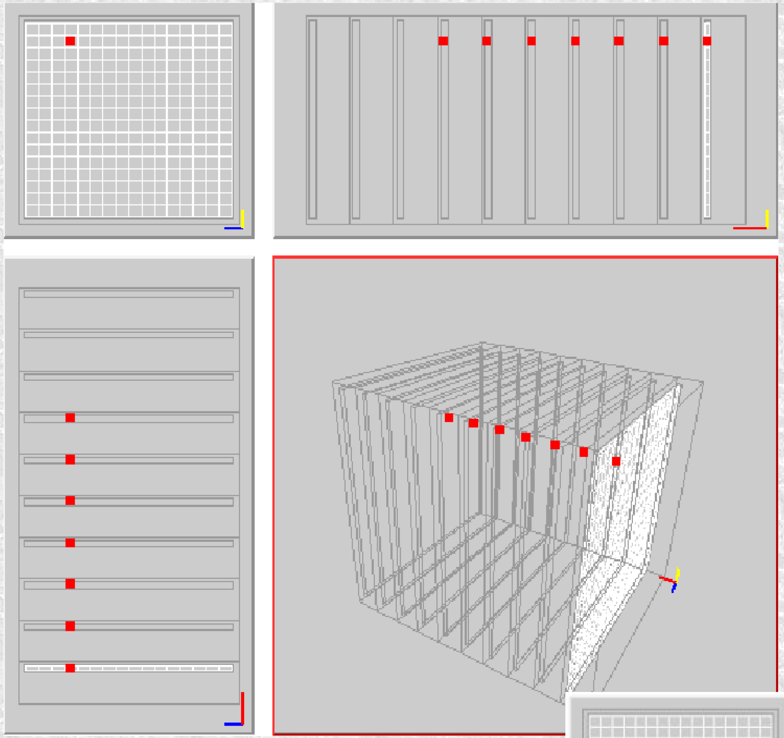
[1] B. Bilki et. al., JINST 3 P05001, 2008.

[2] B. Bilki et. al., JINST 4 P04006, 2009.

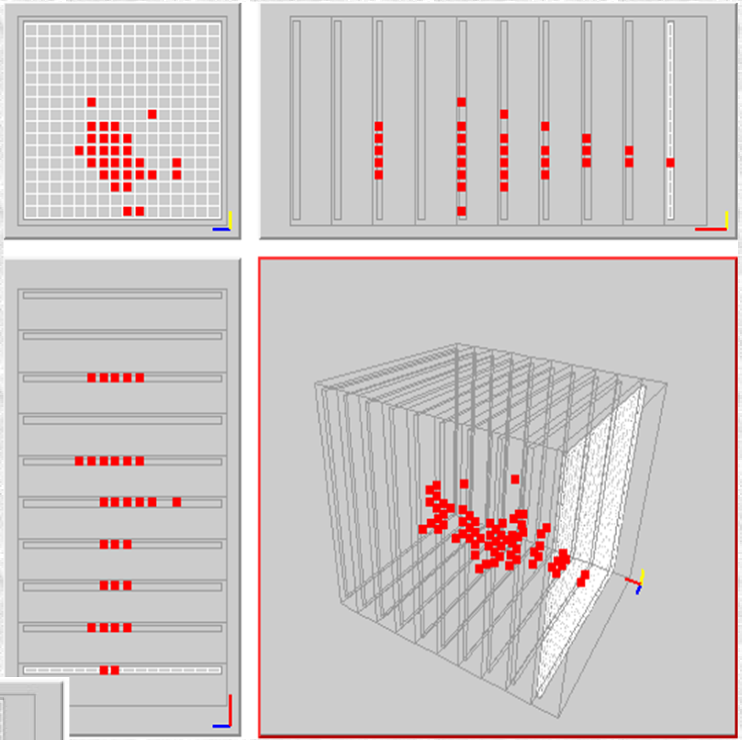
[3] B. Bilki et. al., JINST 4 P10008, 2009.

[4] B. Bilki et. al., JINST 4 P06003, 2009.

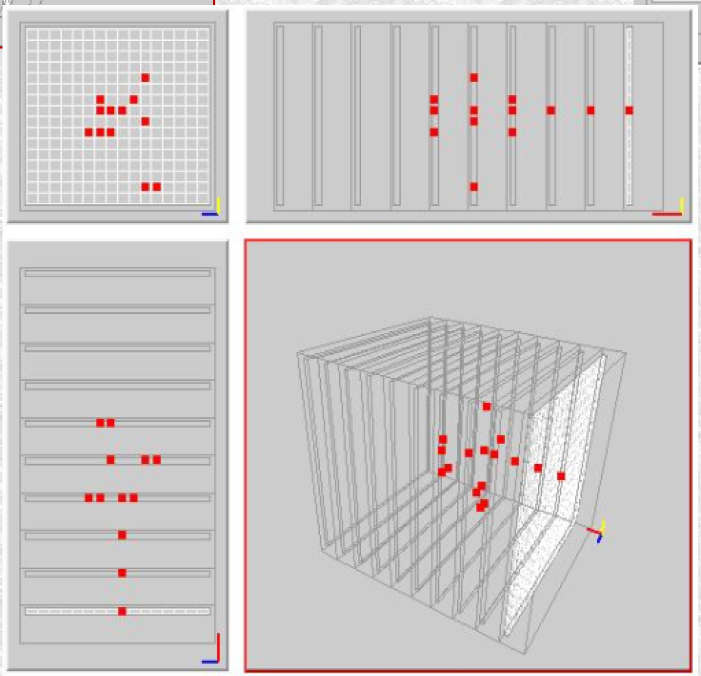
Sample Events



muon

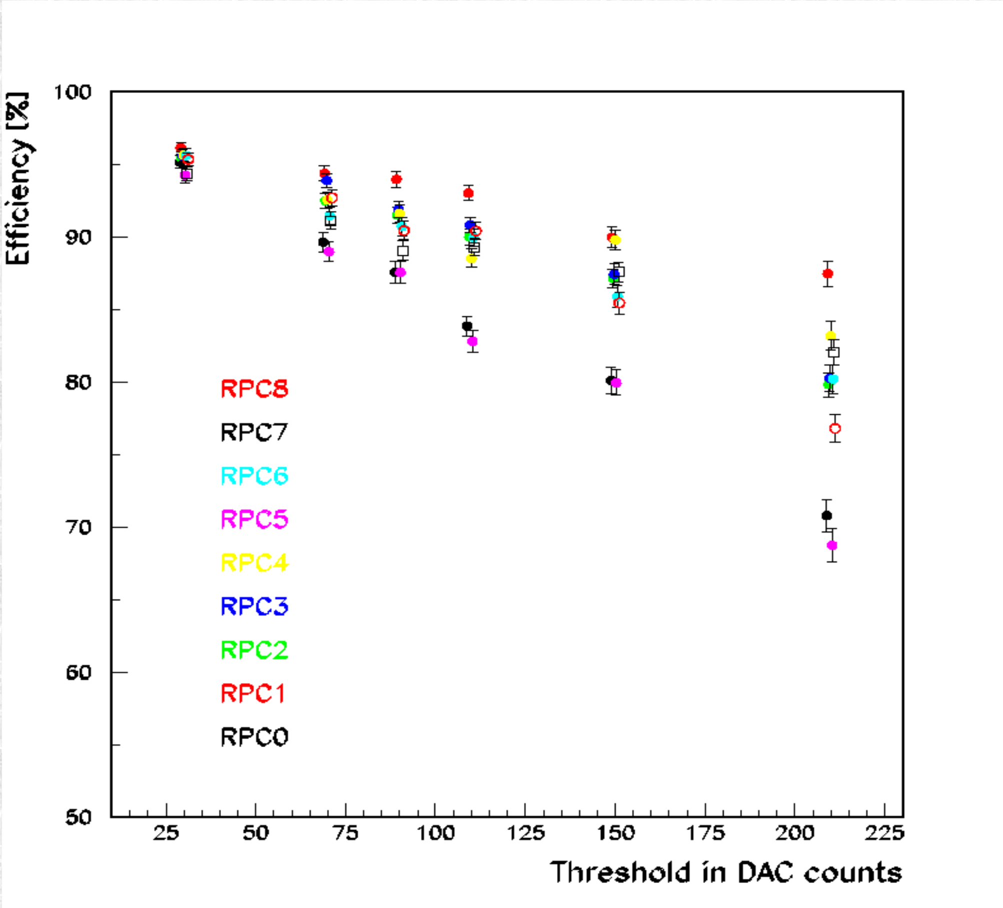


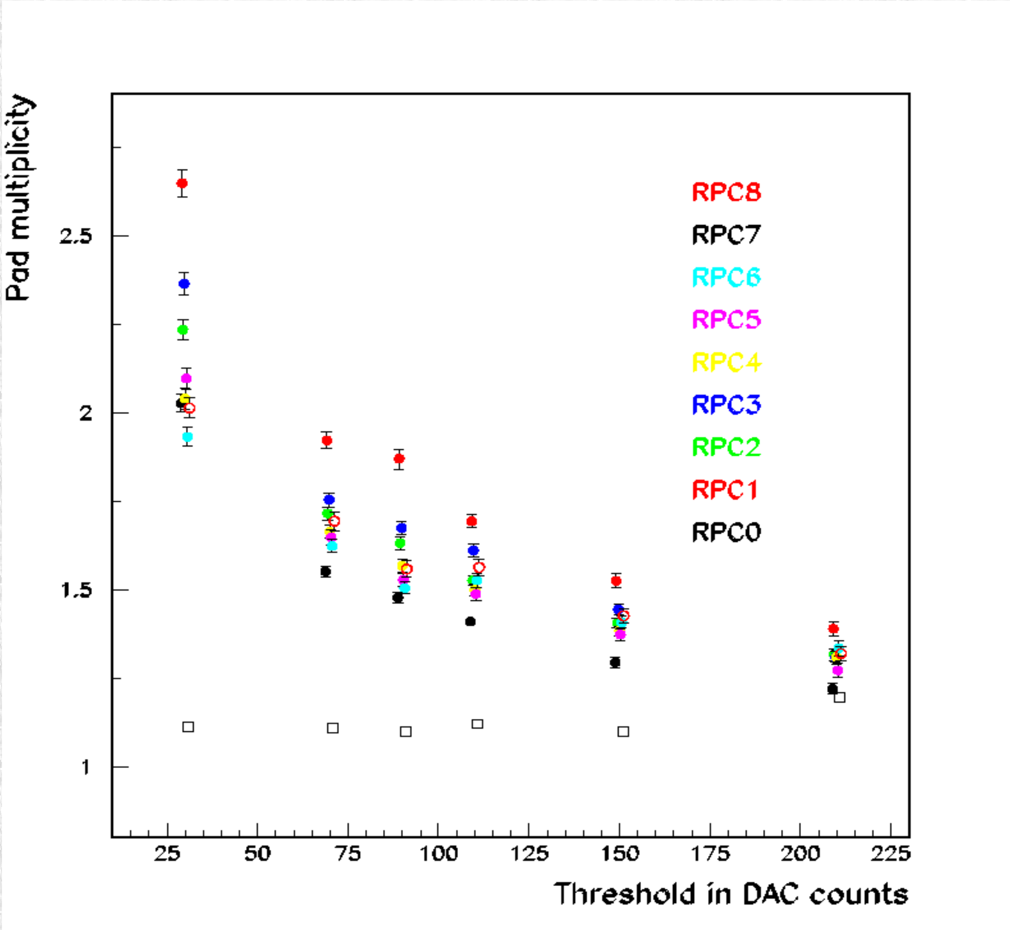
8 GeV e+



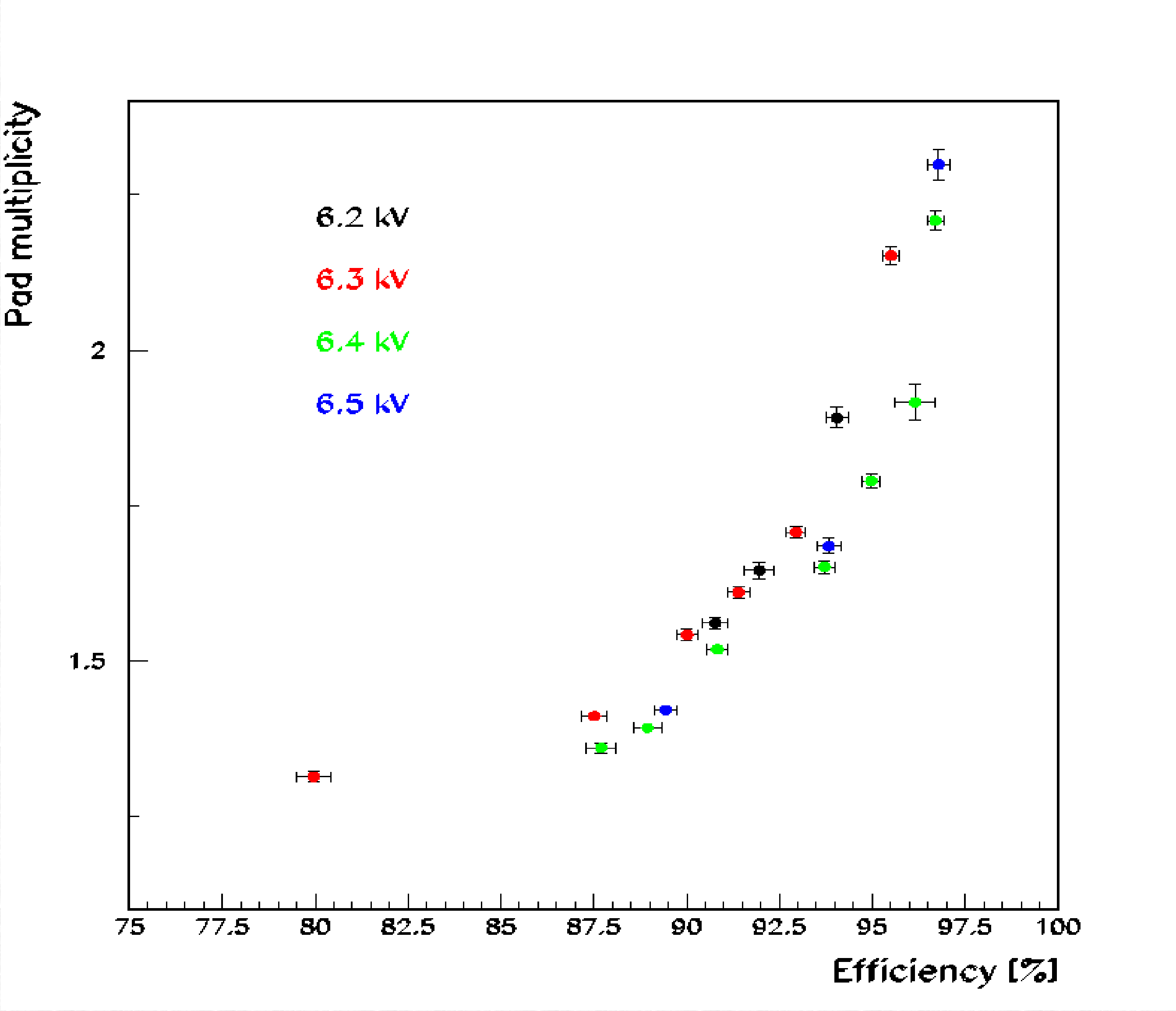
8 GeV pi-

Dependence on Threshold

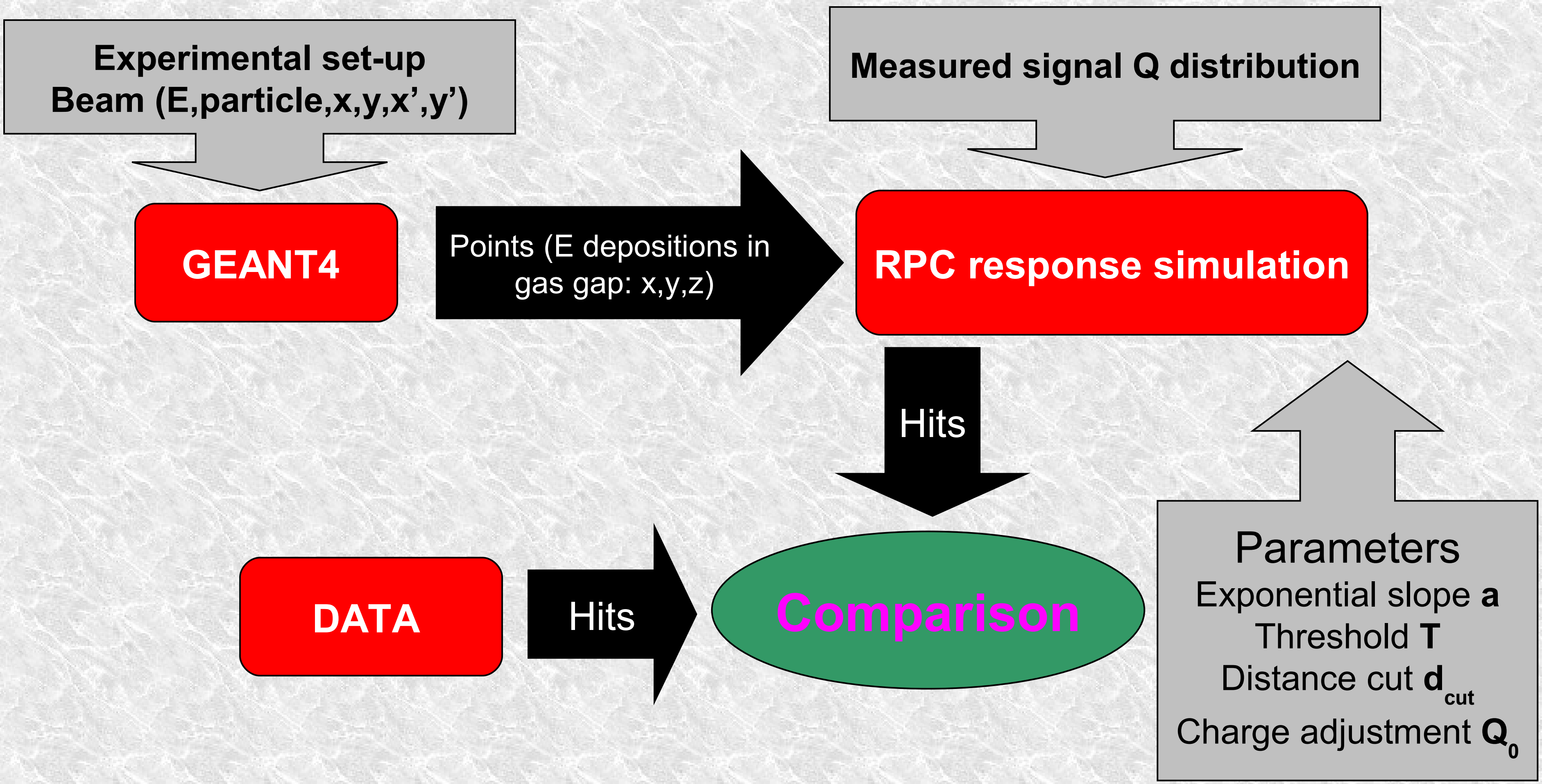




Dependence on High Voltage



Simulation

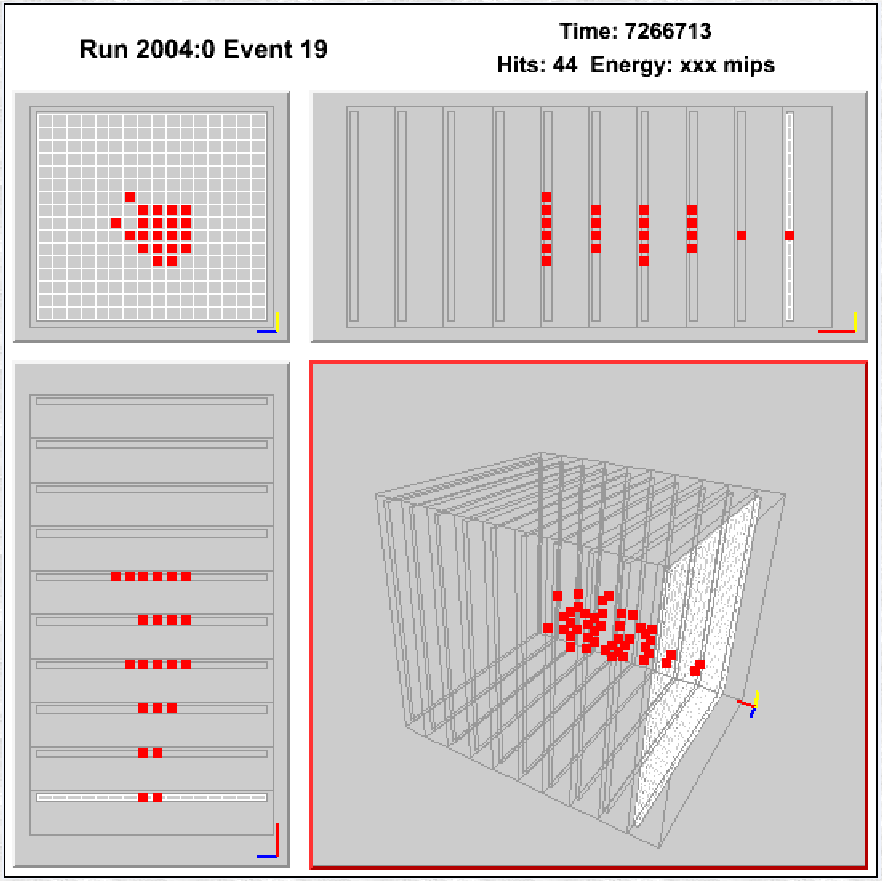


With muons – tune **a**, **T**, ($\mathbf{d}_{cut}$), and $\mathbf{Q}_0$

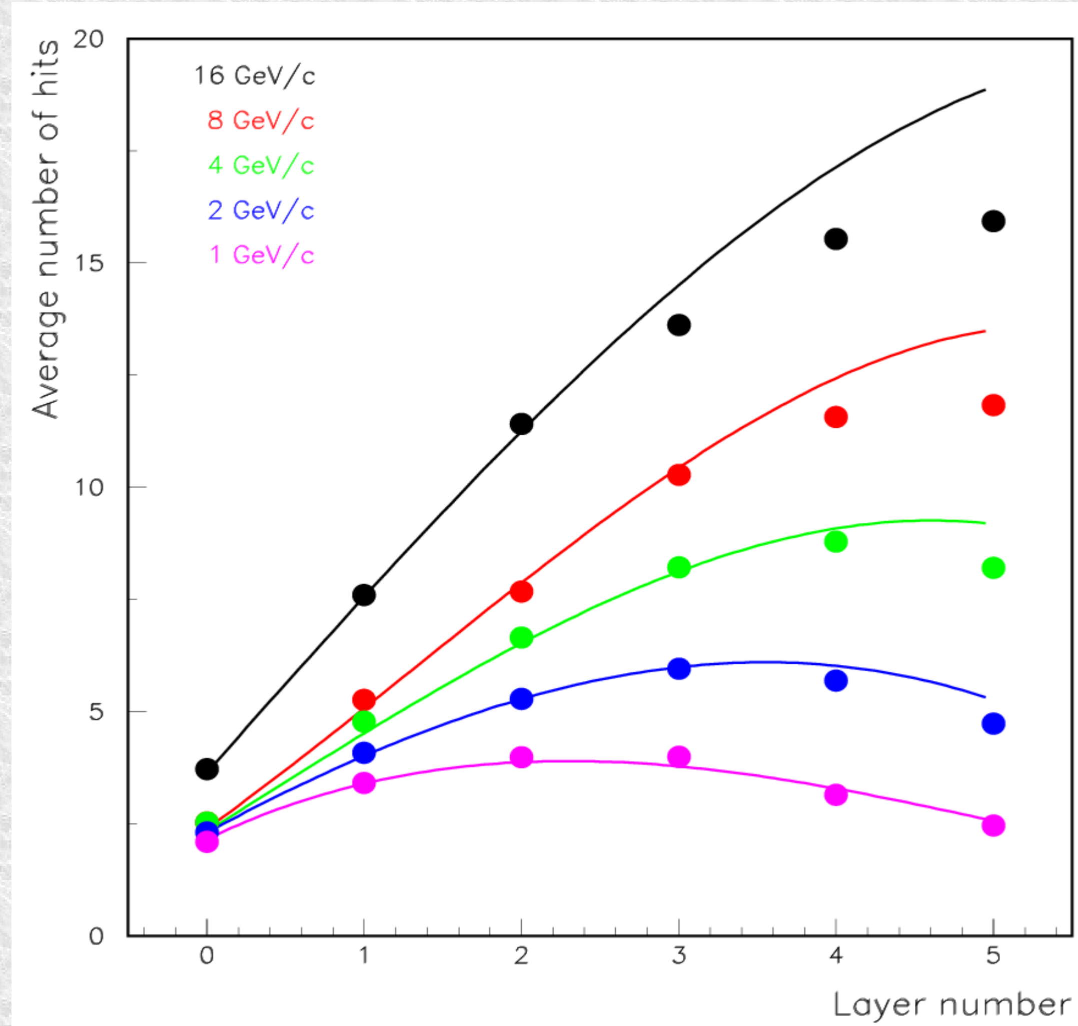
With positrons – tune $\mathbf{d}_{cut}$

Pions – no additional tuning

Measurement of Positron Showers

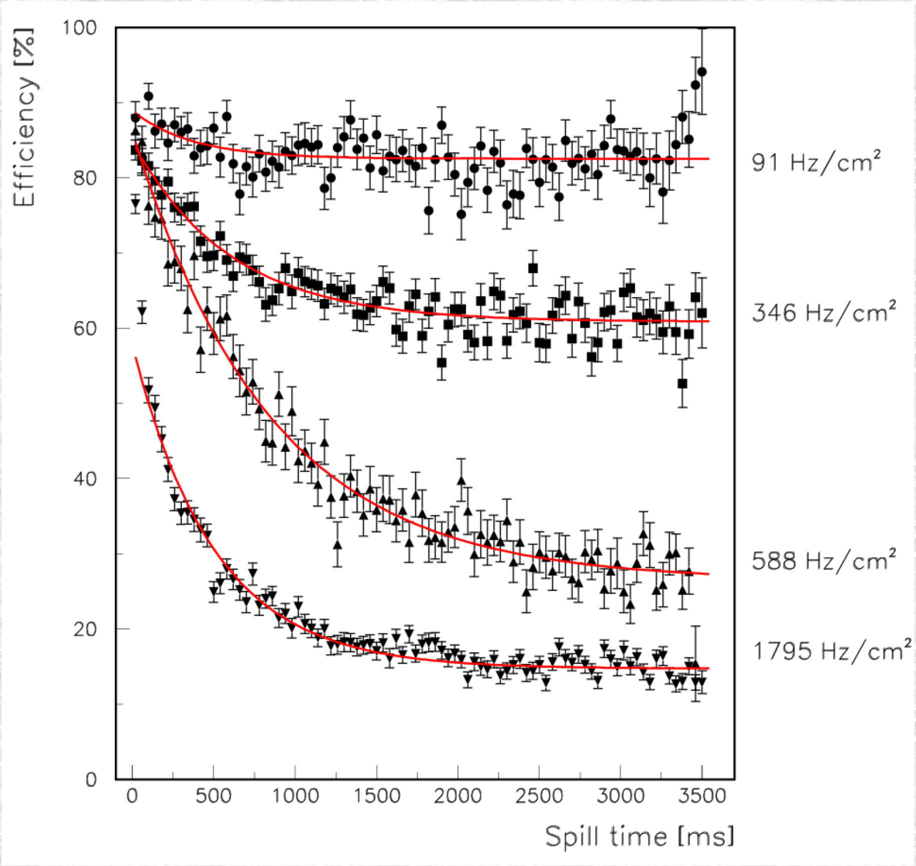


Event display of a positron-induced shower.

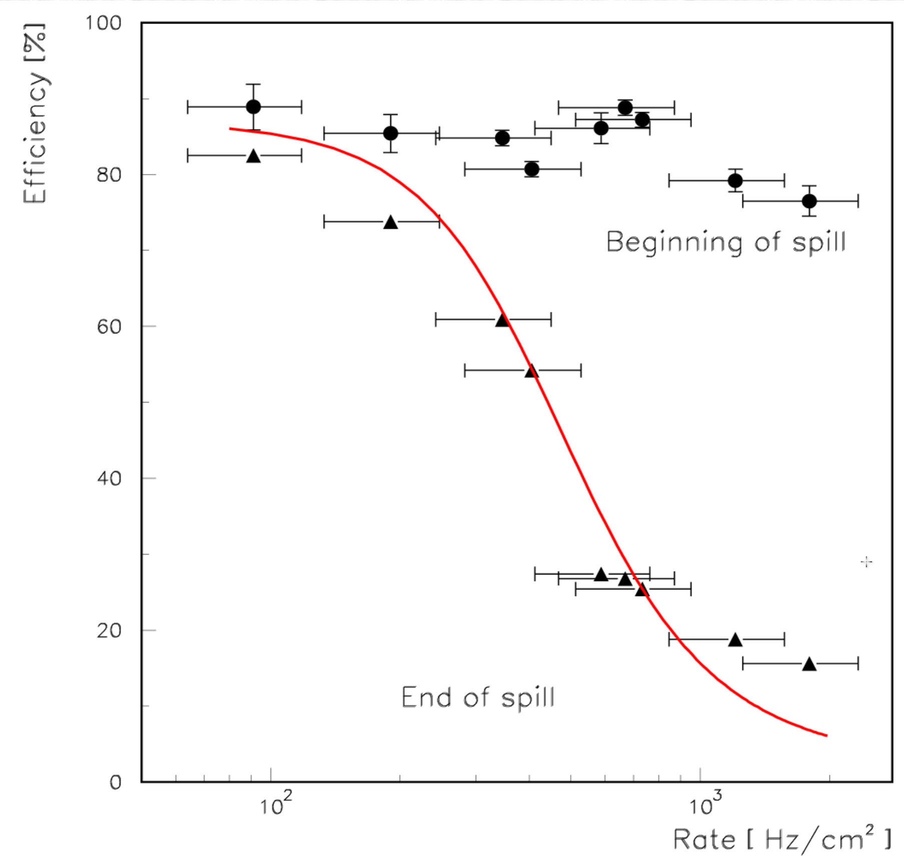


Average number of hits as a function of layer number for the various beam energies. The lines represent the results of a GEANT4 simulation of the set-up together with the simulation of the response of RPCs with a standalone program (RPCSIM by J. Repond).

Rate Measurements



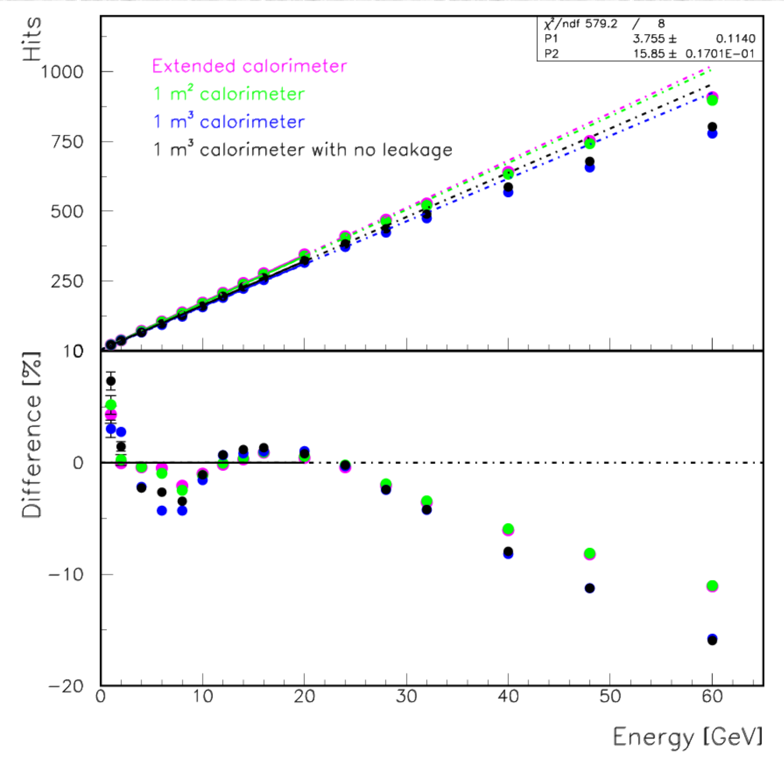
MIP detection efficiency as a function of spill time for various beam intensities. The red curves are fits to the data using the sum of an exponential and a constant.

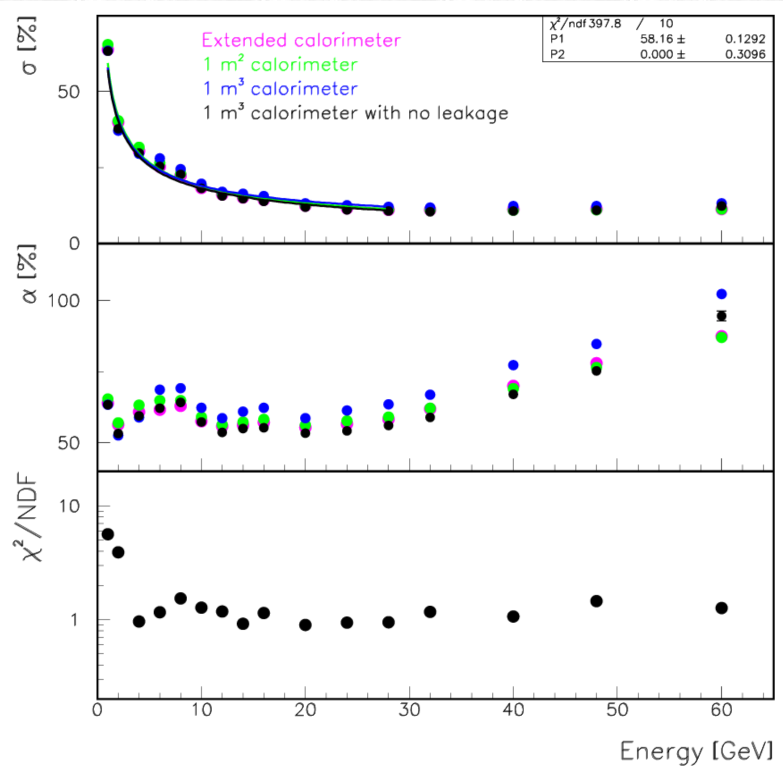


MIP detection efficiency as a function of beam intensity at the beginning (squares) and the end (triangles) of a spill.

We have developed a simple model which predicts an exponential drop of efficiency followed by a constant value. The red curve on the right plot is an absolute prediction.

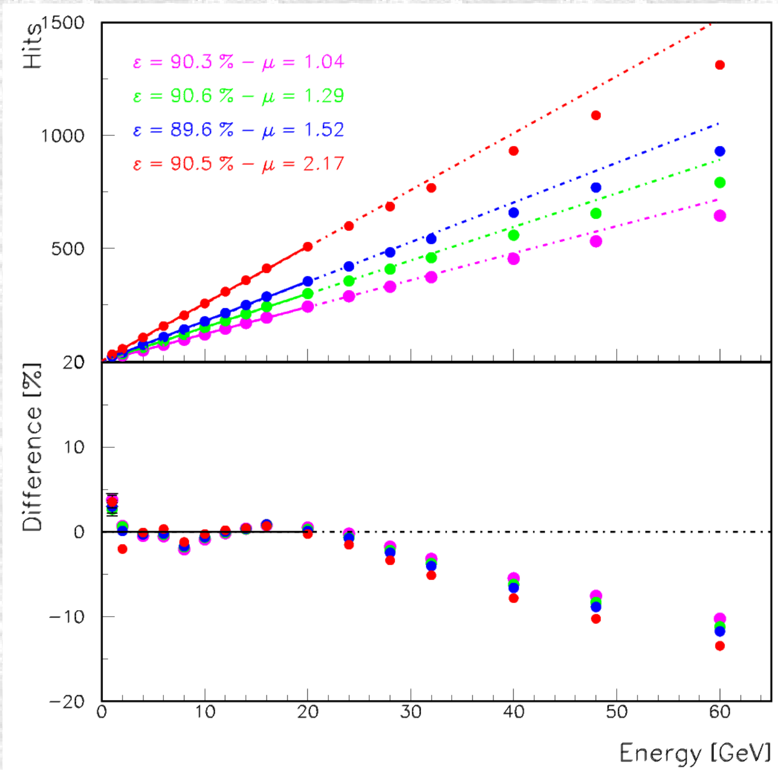
Simulating Larger Systems

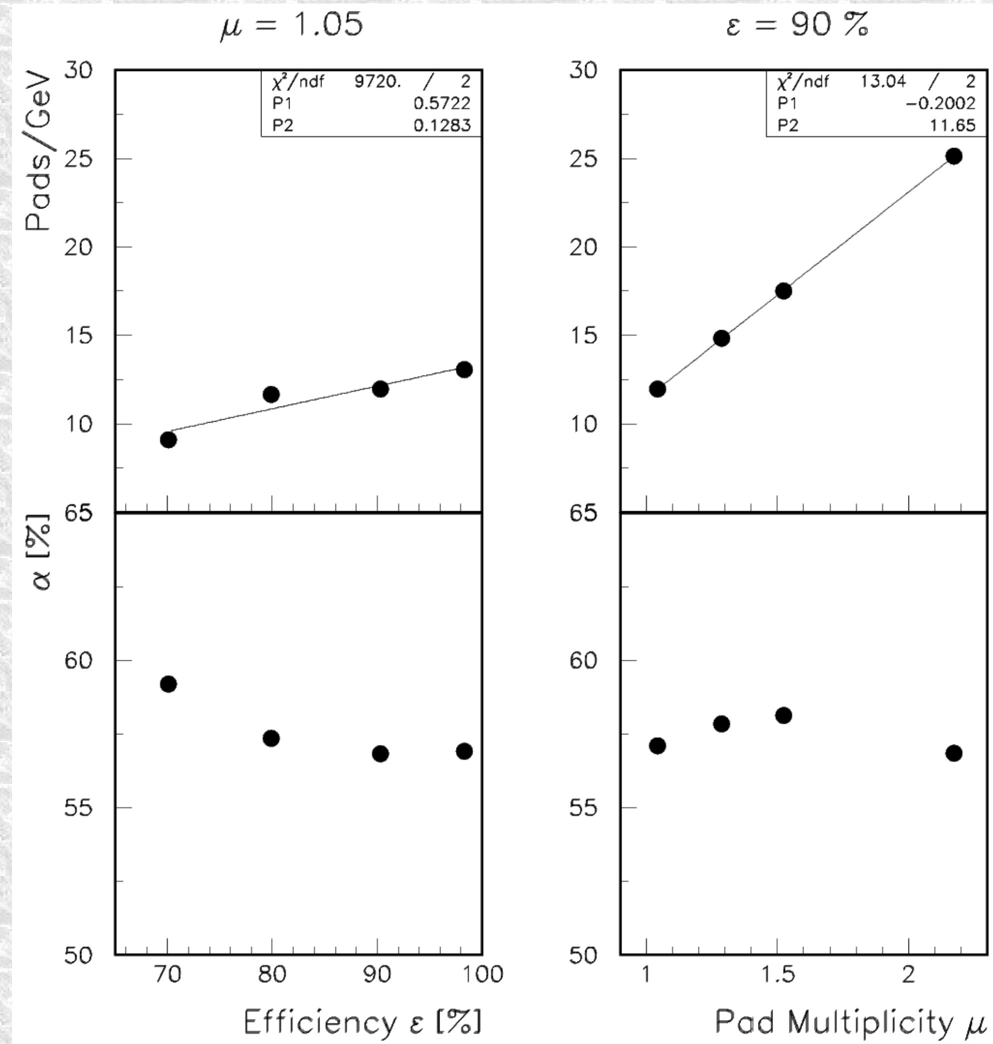




Two different physics packages for 1 m^3 simulations.
Reasonable Gaussian fits for E > 2 GeV
Resolution ~ 58%/√E(GeV) (for E < 28 GeV)

Study of Different Extended RPC-Based Calorimeters





Efficiency and pad multiplicity have only minor effect on resolution

Linear calibration corrections for ε, μ will work

Conclusions

- **Background Noise:** Using the self-triggered mode of the front-end readout, the rate was established to be typically 0.15 Hz/cm^2. The probability of such a noise hit overlapping with e.g. a 300 ns readout window, as used in triggered mode, is negligible.

- **MIP Detection Efficiency:** Depending on the high voltage and threshold settings, efficiencies in the range between 80% and 96% were obtained using track segments reconstructed in neighboring layers. As expected the efficiency drops around the location of the two fishing lines located in the gas volume. Lower values of the efficiency observed in two of the chambers were later explained as being related to the particular grounding scheme used during the test beam data taking.

- **Pad Multiplicities:** Depending on the high voltage and threshold settings pad multiplicities between 1.2 and 2.2 were measured using track segments in neighboring layers. With the 'exotic' chamber pad multiplicities around 1.1 were obtained, independent of the operational conditions.

- **Rate Effects:** At beam intensities in excess of 100 Hz/cm^2, the efficiency is seen to decrease exponentially with time after the beam turns on, until reaching a constant value. A simple calculation based on the voltage drop in the gas gap due to the current flow through the chamber at high rates reproduces the main features of the observed loss in efficiency as a function of spill time.

Conclusions

The physics of the Digital Hadron Calorimeter with Resistive Plate Chambers has been understood to a very satisfactory level.

We are now in the progress of building a 1 m^3 DHCAL with 40 layers of RPCs and ~ 400,000 readout channels. University of Iowa is responsible for High Voltage and gas systems which are almost complete.

This prototype will then be tested in Fermilab test beam.

Conclusions

The advantages of a high segmentation calorimeter with digital readout can be seen even with the small size prototype. Such a calorimeter system allows the use of sophisticated algorithms (such as PFAs) that will lead to an achievement of jet energy resolutions around 30%. This perfectly fits into the physics program of the Muon Collider as a robust, efficient and radiation hard calorimetric solution that has negligible noise and background interference and well-understood performance characteristics and environmental dependence.