Silicon Tungsten Calorimeters The WIZARD experiments

– PART II –

G. Zampa, M. Boezio, V. Bonvicini, E. Mocchiutti, A. Vacchi, N. Zampa
(INFN-Sezione di Trieste, Italy)

OUTLINE

- The PAMELA Si-W calorimeter electronics
- Developments for future space calorimeters
- FE electronics for the NCC: considerations

INFN Istituto Nazionale di Fisica Nucleare Sezione di Trieste

The PAMELA Si-W Calorimeter

- Extraction of the antiproton signal from the background of electrons and identification of the positrons from the proton background
- Rejection factor better than 10^4 with a selection efficiency > *90%*
- Measurement of the electron's and positron's energy with a resolution better than 10%
- Three-dimensional reconstruction of the spatial development of the showers

- Modular sampling Si-W calorimeter with high granularity (W thickness $2.6\ mm, \rightarrow 0.74\ X_0$)
- Transverse segmentation: ≈ $2.4\ mm$ strip pitch
- Si detector: $8x8\ cm^2$, $380\ \mu m$ thick
- Sensitive area: $24\ x\ 24\ cm^2$
- Total Depth: $16.3\ X_0$, $0.6\ \lambda_0$, *22* layers Si-X/W/Si-Y
- Total number of channels: *4224*
- Self-trigger to study the electronic component up to $2\ TeV \rightarrow$ geometric factor ≈ $600\ cm^2 sr$, *30* times larger than PAMELA

INFN Istituto Nazionale di Fisica Nucleare Sezione di Trieste

Calorimeter electronics: requirements

The calorimeter will operate in orbit → radiation environment:

– Total Ionizing Dose: 3 krad inside the PAMELA container

– Possible Single Event Effects: LATCH-UP and UPSET (digital logic)

Therefore:

→ commercial electronic devices tested up to 30 krad

→ fault tolerant design and use of redundancy

Data storage allocated for PAMELA: 10G byte per day

– expected average trigger rate of 12 Hz
– more than 40000 read-out channels

} > 80G byte every day

Digital processing to:

– Compress the event data

– Reduce the trigger rate discarding non interesting events

The CR1.4P: requirements & design specs

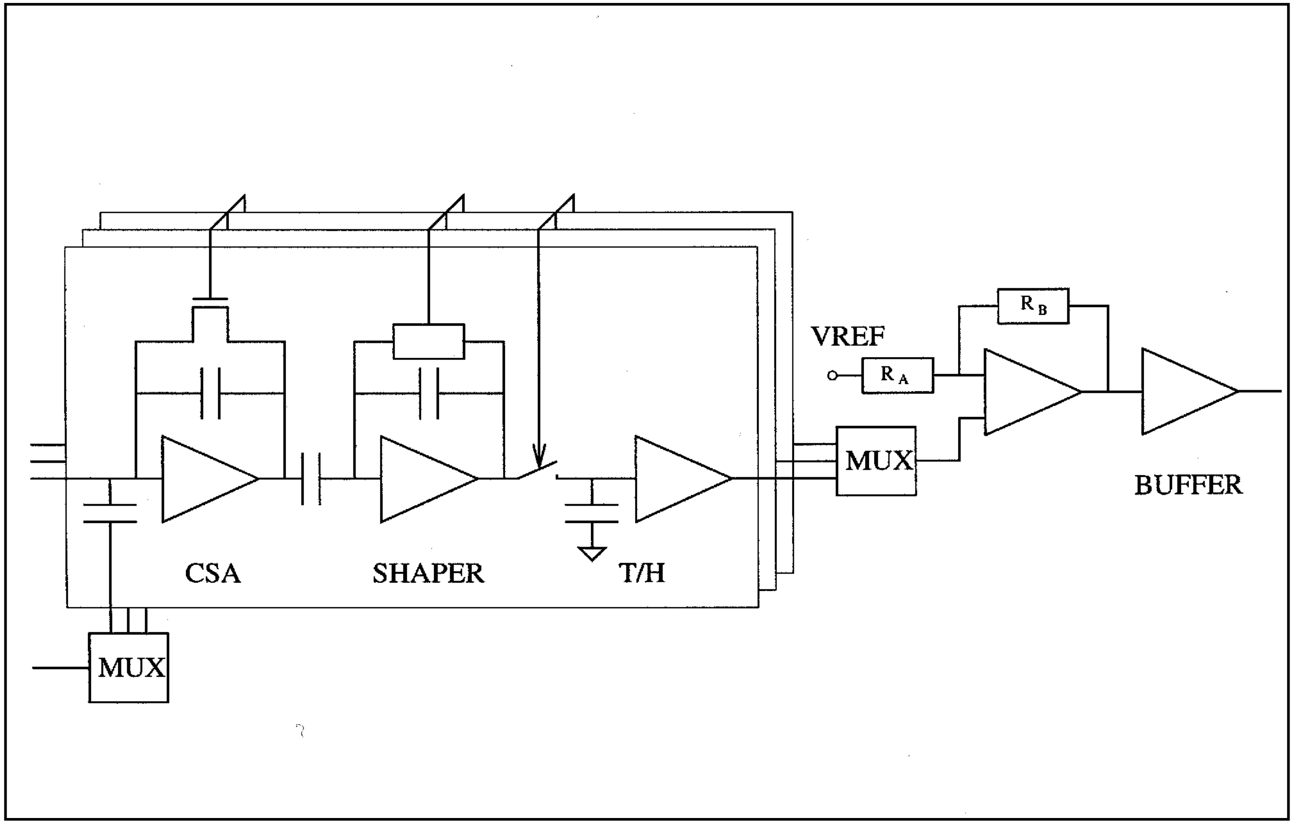
- Low power budget available (<u>50 W for CALO!</u>) → **Low power cons.**
- Measure interactions of very high energy particles → **> 1000 MIPs range**
- Measure non-interacting particles with high precision → **At least 8:1 on 1 MIP**
- Large detector capacitance, $C_D \approx 180$ pF → **Low noise slope**

<u>Circuit design specs</u>:

- Supply	+/- 5 V
- Number of channels/chip	16
- Maximum power consumption	100 mW/chip
- 1 MIP	4.9 fC = 30500 e^-
- Linear dynamic range	1400 MIPs
- Maximum output signal	7 V
- Sensitivity	5 mV/MIP
- Maximum detector leakage current	100 nA
- Peaking time	1 µs
- Detector capacitance	180 pF
- ENC_{max} @ 180 pF	3000 e^- rms
- Integrated calibration capacitance	2 pF
- Logic levels	0/+5 V TTL
- Channel-to-channel pedestal variation	+/- 50 mV
- Chip-to-chip pedestal variation	+/- 100 mV
- Readout speed	0.5 µs/channel
- Output load	20 kΩ//25 pF
- Counting rate	30 kHz

The CR1.4P: general architecture

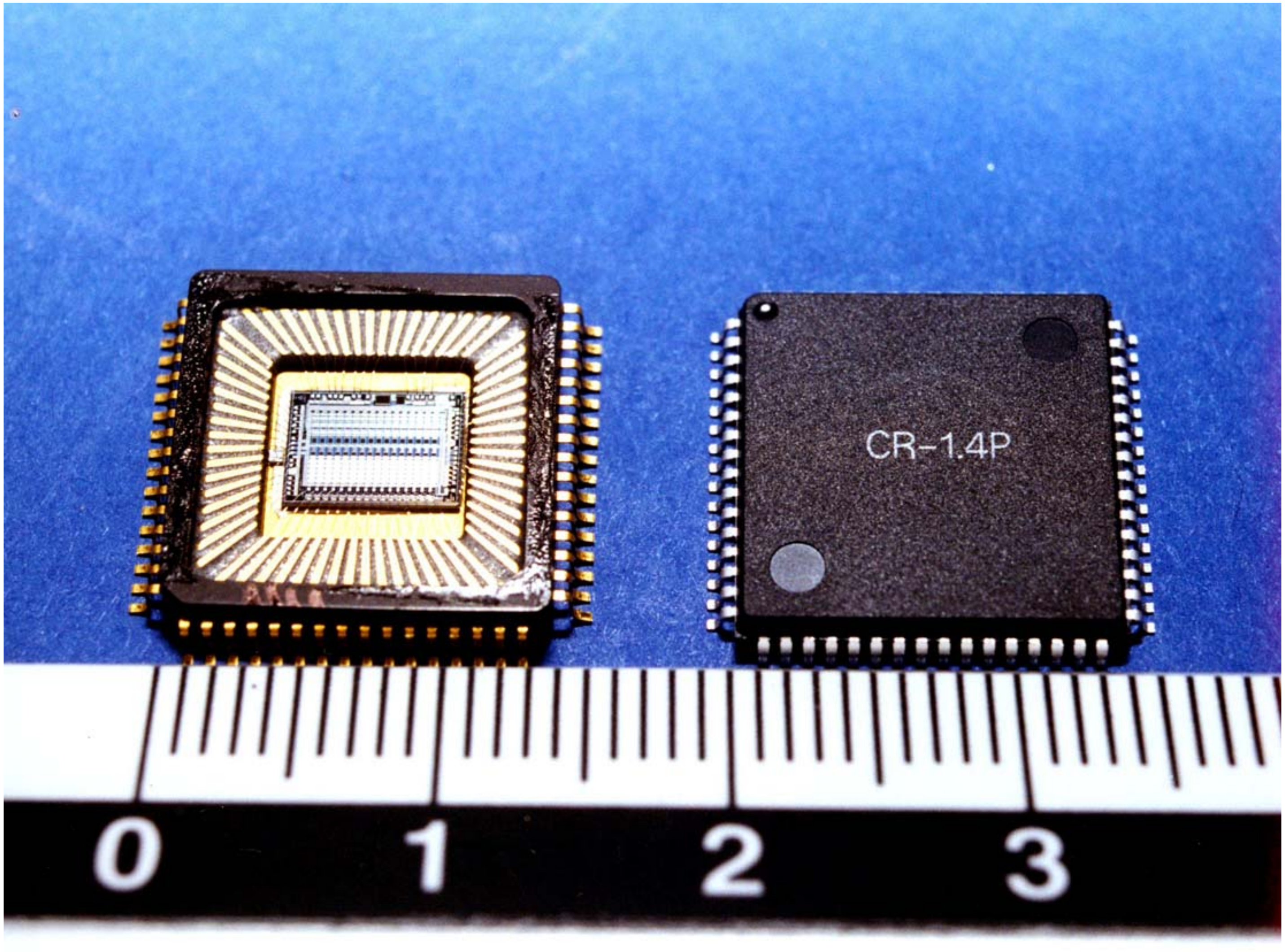
- Alcatel/Mietec 2 um mixed A/D CMOS;
- Input calibration ciruit;
- “Folded cascode” CSA;
- C_f = 8 fF;
- PMOS charge reset;
- CR-RC shaper, 1 μs peaking time;
- T/H circuit + buffer;
- Output MUX;
- “X2” output stage with DC bias;
- Self-trigger circuit (not shown here)



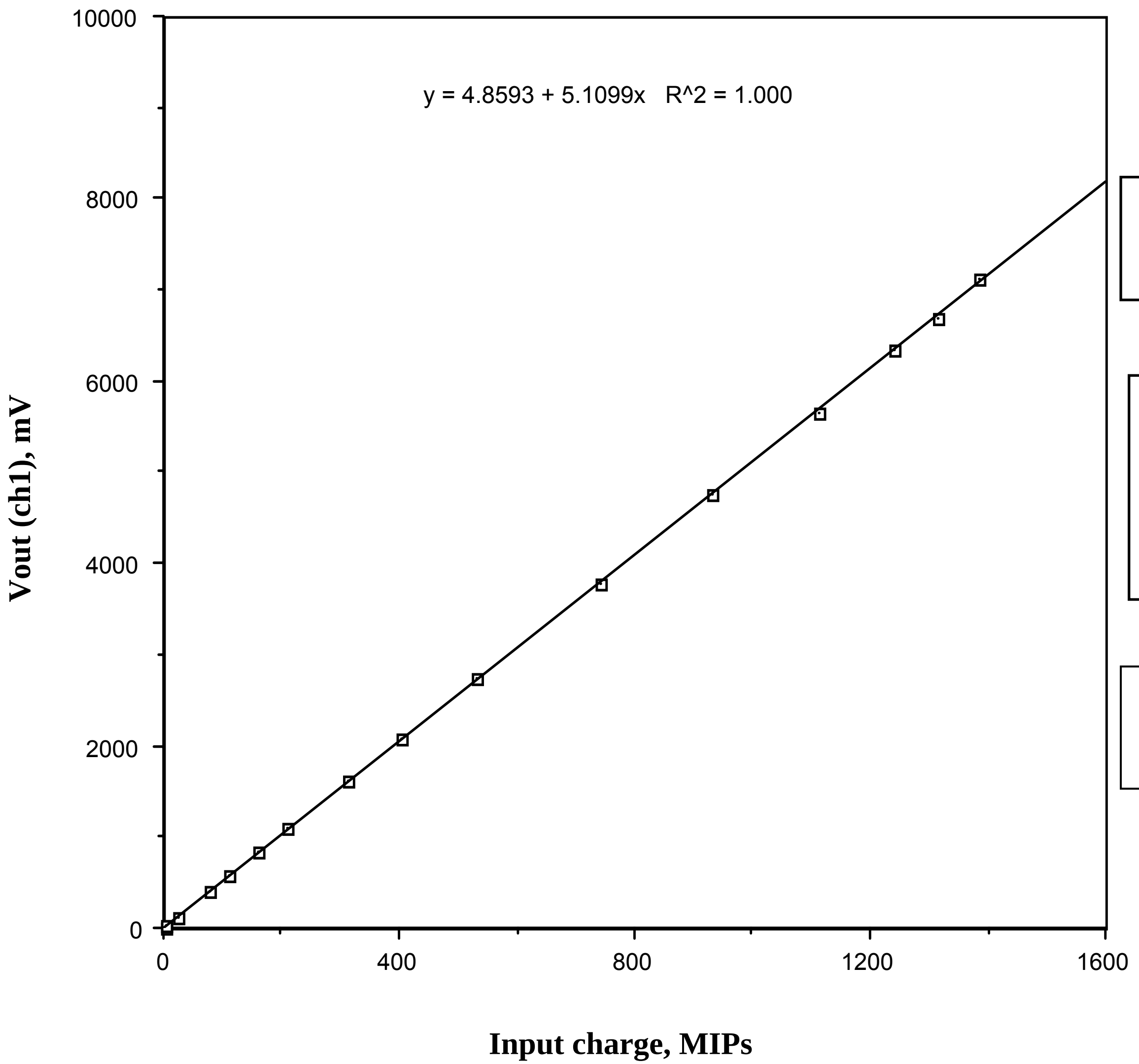
Architecture of a single channel of the CR1.4P

R&D phase from 1996 to 1998 (3 different prototypes tested)
10 wafers (about 1300 chips) produced between 1998 and 2000
Total yield > 70%
264 chips equip the FM of the PAMELA Calorimeter
Adopted also by the PAMELA TRD

INFN Istituto Nazionale di Fisica Nucleare Sezione di Trieste


CR-1.4P
0
1
2
3

Linearity and dynamic range



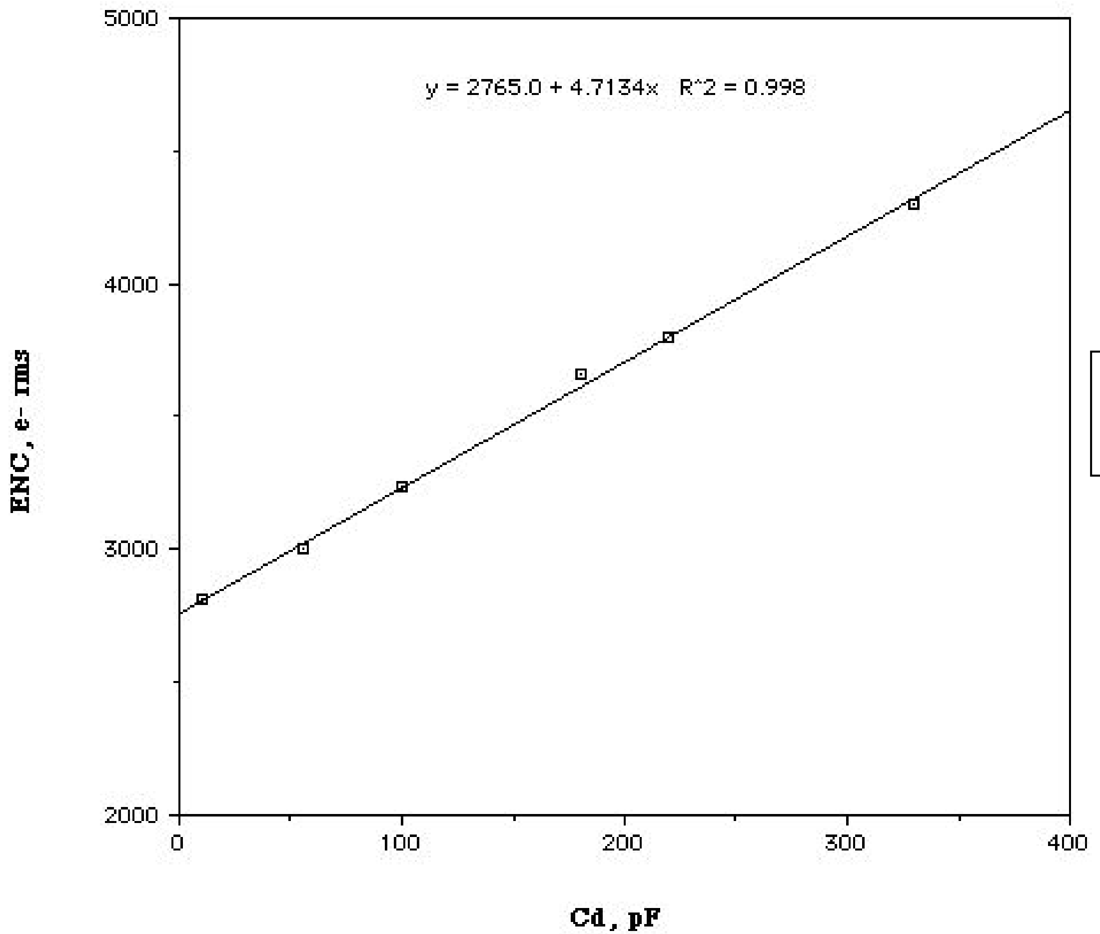
CR1.4P

sensitivity 5.1 mV/MIP
R_f(CSA)=630 kΩ

Max. deviation from linear fit < 2.5 %
average linearity better than 1 %

Linear dynamic range 1400 MIPs or 7 pC

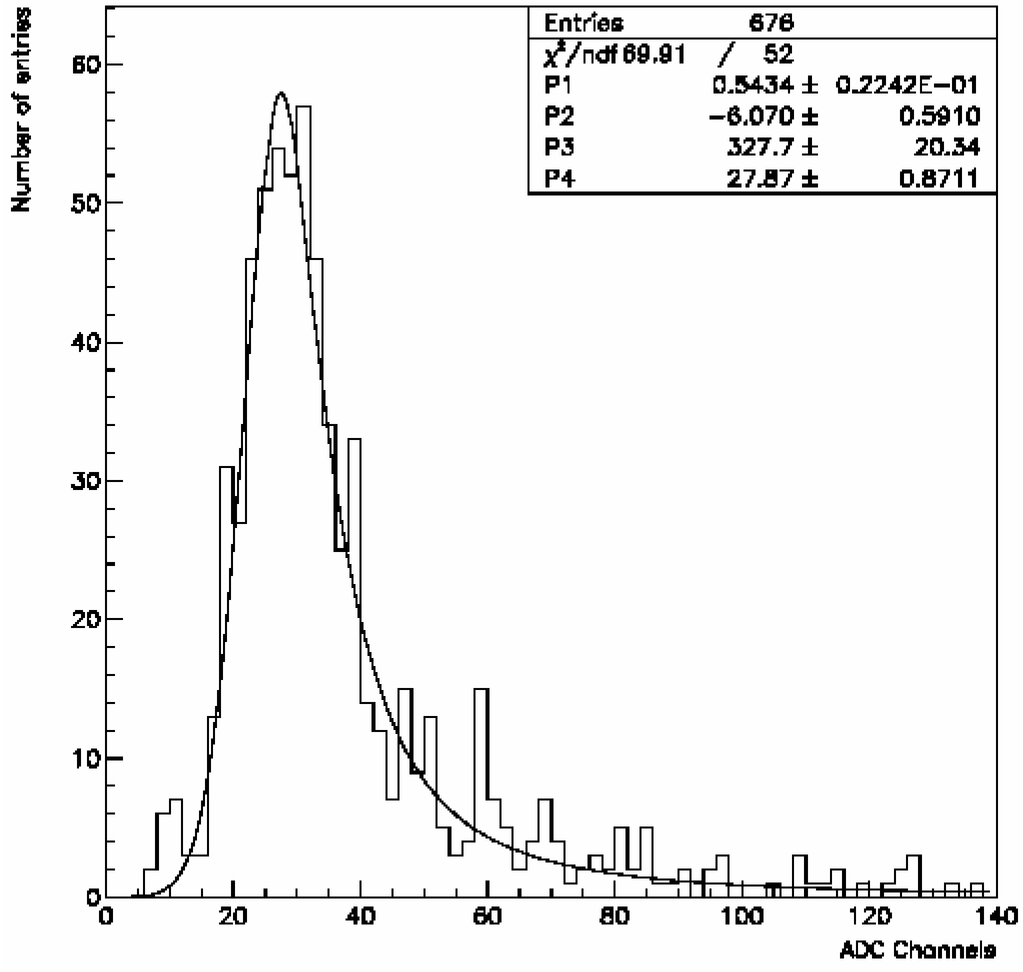
Noise



CR1.4P

Measured noise
2765 e^- rms + 4.7 e^-/pF

Performance in operational conditions



MIP signal from cosmic muons, Gaussian + Landau fit, S/N ≈ 9/1
Data taken during pre-integration tests of the FM Calorimeter

INFN Istituto Nazionale di Fisica Nucleare Sezione di Trieste

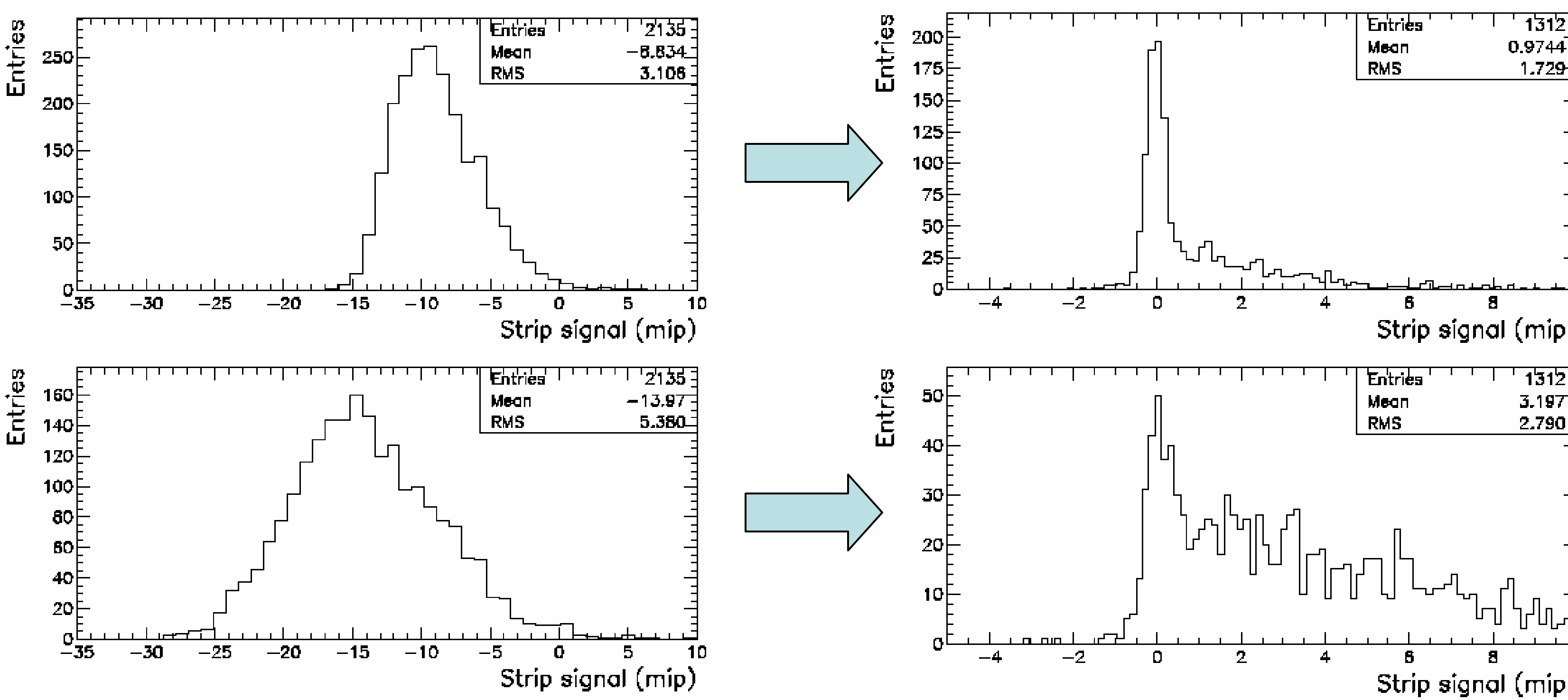
Cross-talk items

Cross-talk effects (occurring in both the detector and the electronics) of different origins become important in case of very large charge deposits and should be accounted for.
3 different "cross-talk" effects:

1. **Coherent negative in the detector (through the bias-ring), linearly with deposited energy, ~ - 0.5%**
2. **Coherent negative in the chip (through the bias circuitry of the shapers), linear with deposited energy, ~ - 0.5%**
3. **Positive on the two closest-neighbour strips ("classical" cross-talk) ~ 1%**

Example (data from June 2002 CERN SPS test beam):

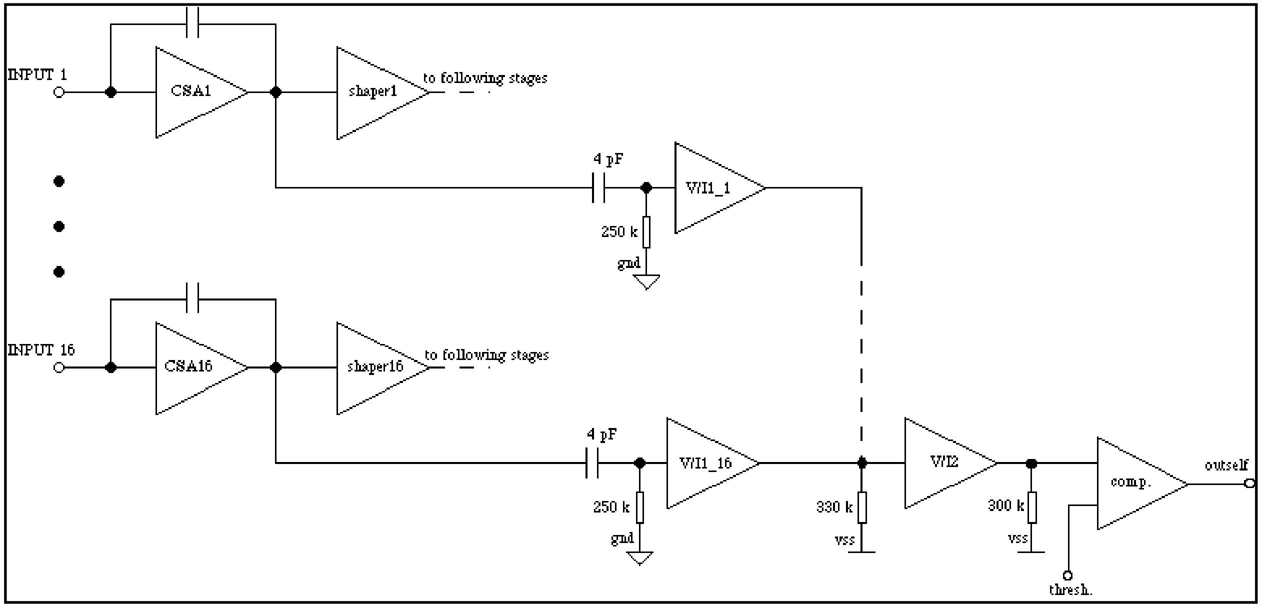
Before correction | **After correction**



Istituto Nazionale di Fisica Nucleare Sezione di Trieste

CR1.4P self-trigger option

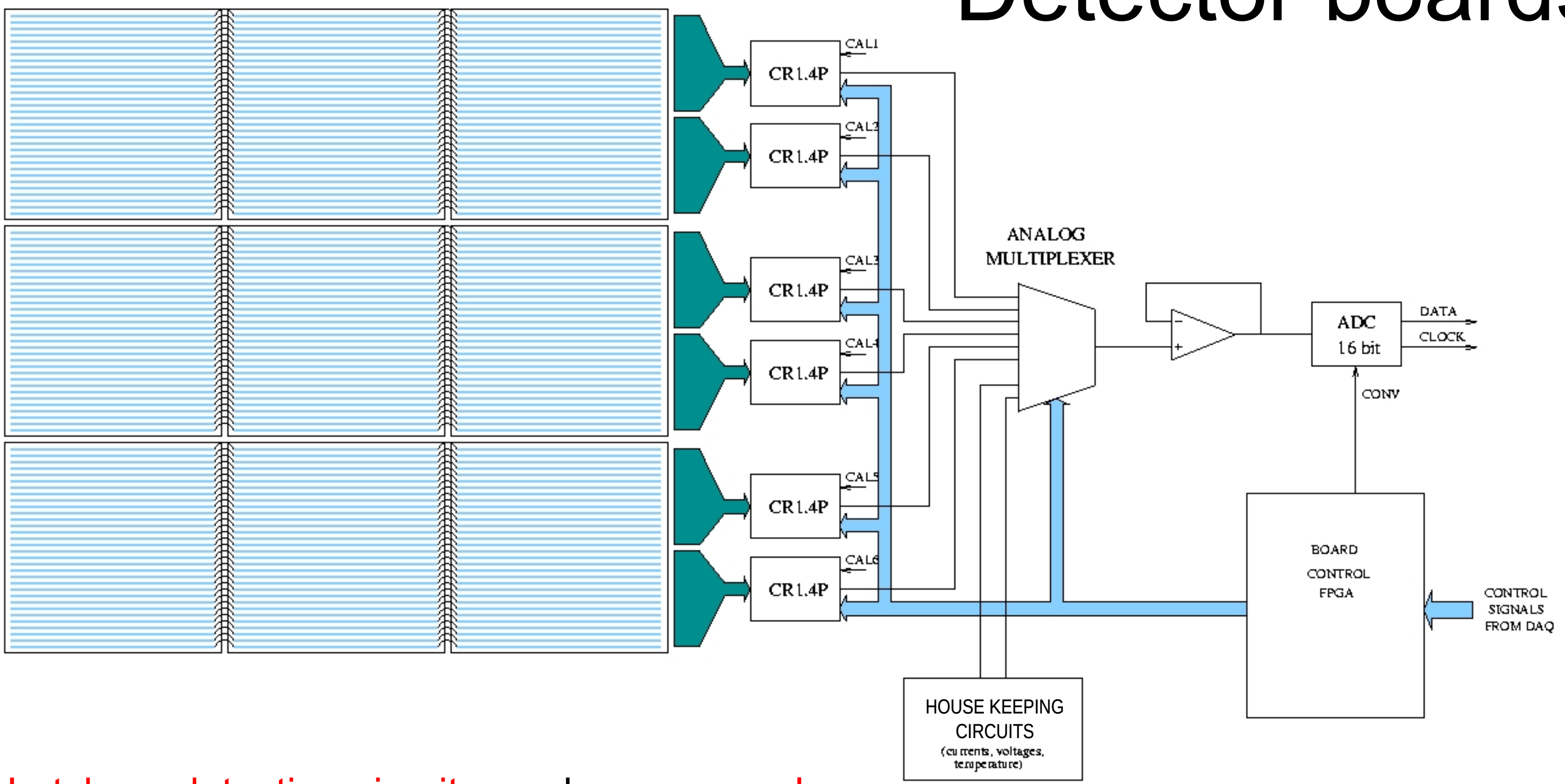
- Science motivation: **measure very high energy electrons (from 300 GeV to ~ 2 TeV)**
- These events are quite rare compared to the normal event rate of PAMELA ⇨ important to have a large geometric factor to collect a reasonable statistics during the 3-year estimated mission lifetime
- Using the calorimeter "stand-alone" can extend the geometric factor of PAMELA from 21 $cm^2 sr$ to ≈ 600 $cm^2 sr$, therefore:
- The CR1.4P was provided also with a "self-triggering" option



Simplified block scheme of the self-trigger circuit in the CR1.4P

INFN Istituto Nazionale di Fisica Nucleare Sezione di Trieste

Detector boards

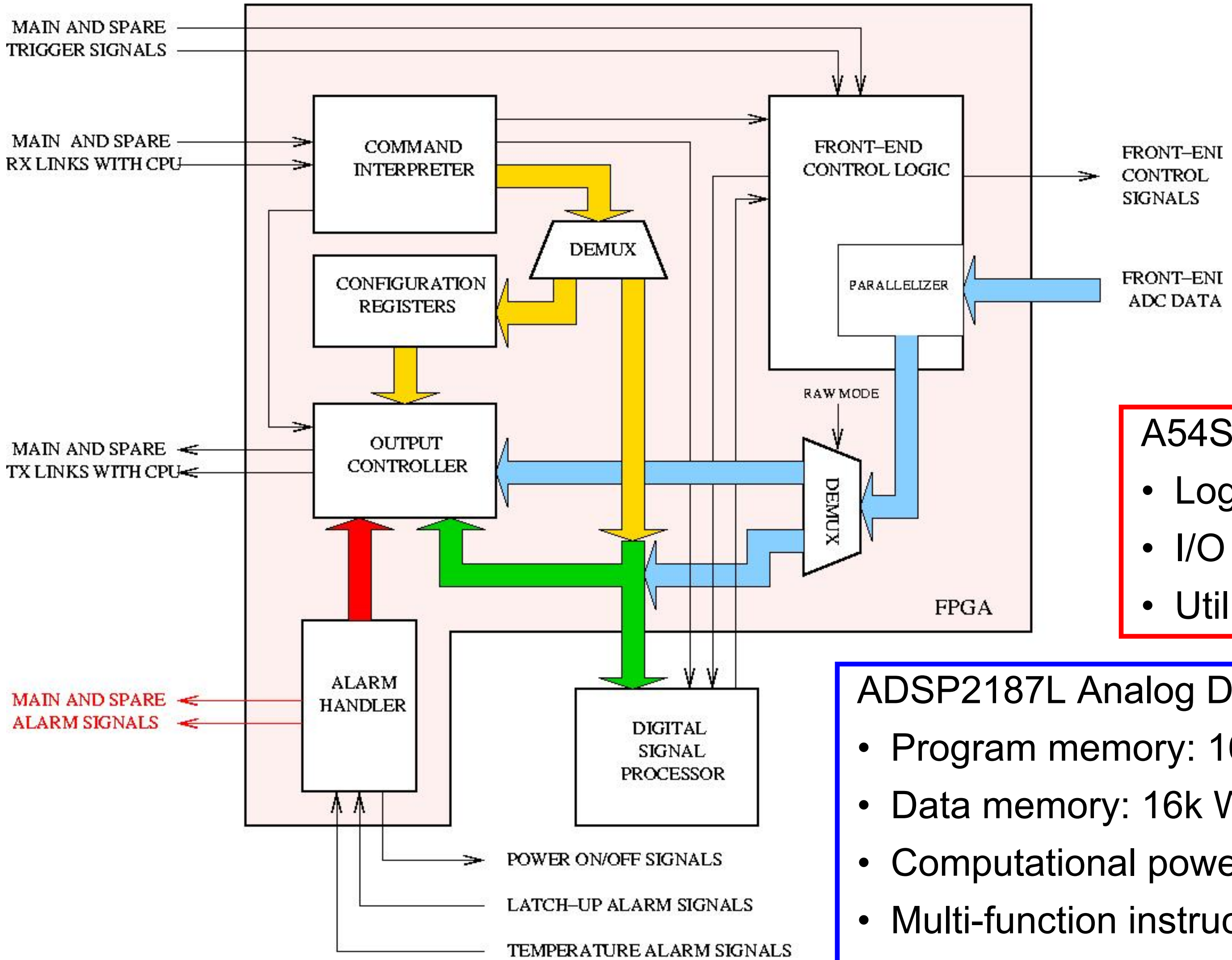


- Latch-up detection circuitry and power supply bus isolation capability
- FPGA: redundant scheme to minimize SEU (triple voting mechanism)
- Short-circuit protection of all common digital signals

AD977A Analog Devices ADC

- Resolution: 16 bit
- Conversion time: 5 μs
- Power consumption: typ. 60 mW
- Serial data interface

DAQ system



A54SX72A Actel FPGA
- Logic gates: 72000
- I/O pins: 171 (PQFP208)
- Utilization: 70%

ADSP2187L Analog Devices DSP
- Program memory: 16k Words (24 bit)
- Data memory: 16k Words (16 bit)
- Computational power: max. 52 MIPS
- Multi-function instructions
- Host interface to access internal memory

Developments for future space calorimeters

- Future astroparticle physics satellite-borne experiments will probe the cosmic rays spectrum at energies up to 10^{16} eV (“knee” region)

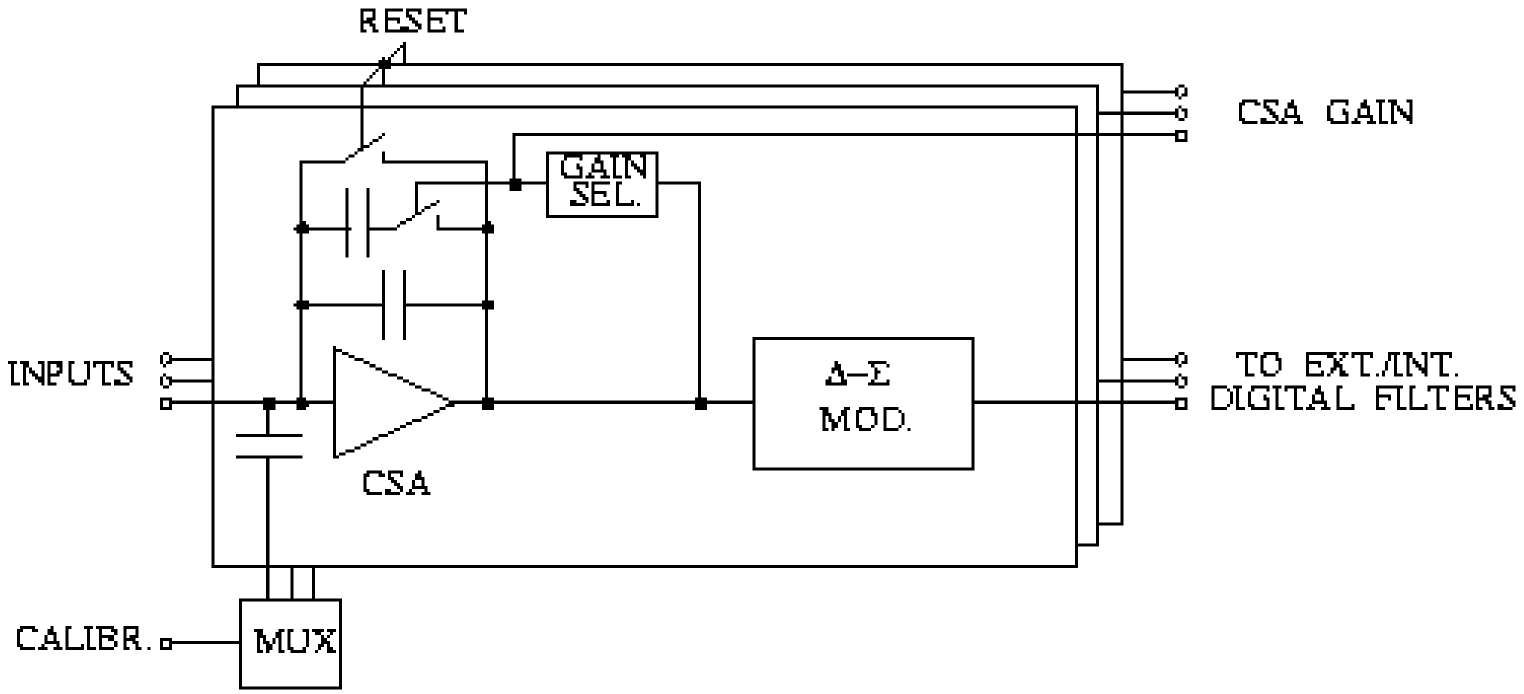
- Depending on the instrumentation that will be used, energy deposits between 10^5 MIP (NUCLEON) and 10^6 MIP (ACCESS) are expected in a readout channel

→ CASIS R&D project: Si detectors and front-end ASICs for high-energy calorimetry in space

KEY ISSUES:

- Space environment → radiation tolerance
- Satellite constraints → low power consumption → low voltage CMOS
- Rare events (1 part./m^2year) → large acceptance → large # of read-out chan.
- Dynamic range ≥ 10000 MIPs → A/D converter integrated in the FE-ASIC

Innovative Front-End architecture

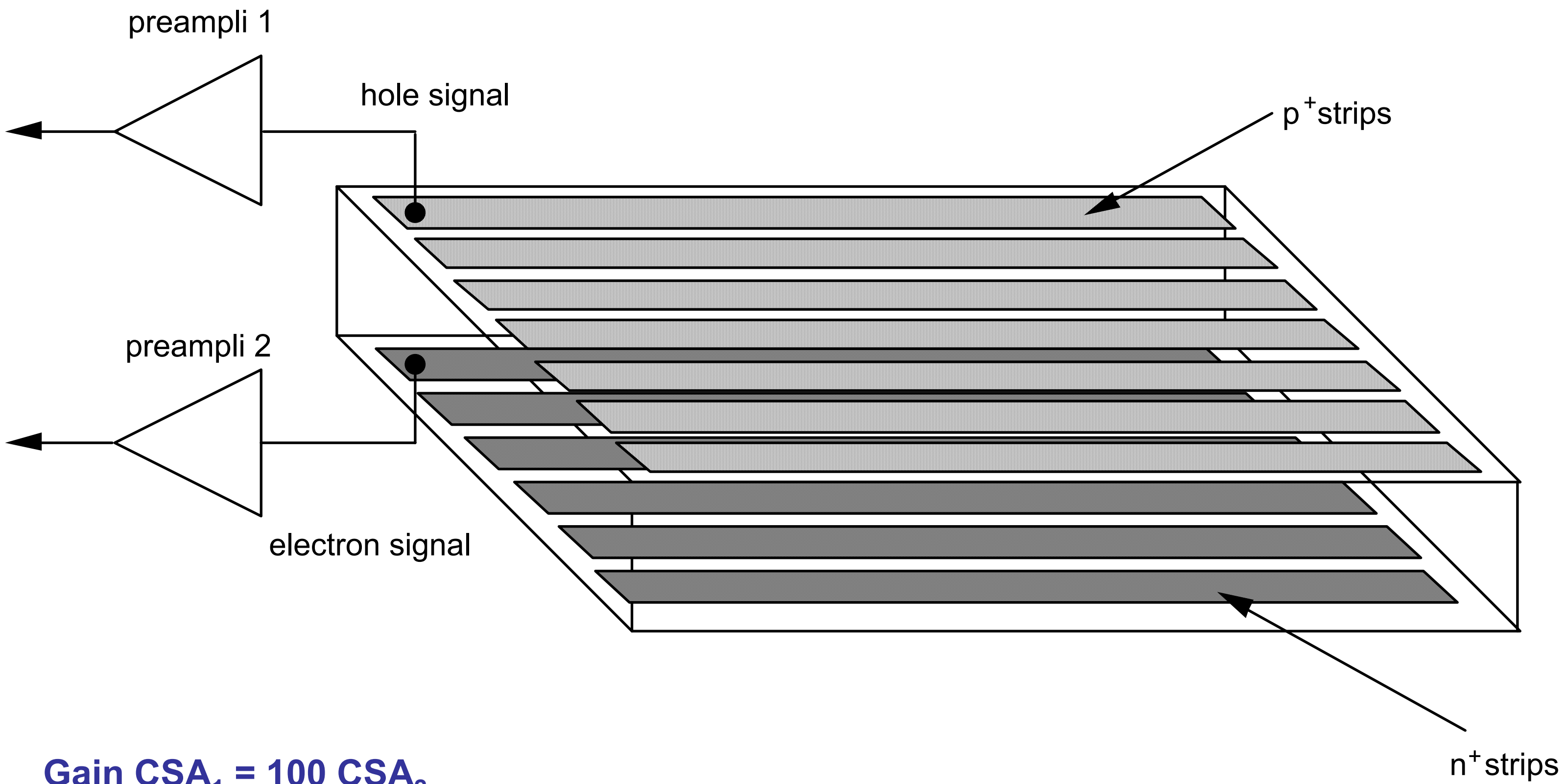


ADVANTAGES:

- A high default gain maximizes SNR for 1-MIP signals
- The modulator is insensitive to gain switch transients
- The modulator efficiently filters the electronic noise (resolution set by the over-sampling ratio)
- Several possible filter implementations: ASIC, FPGA and DSP

INFN Istituto Nazionale di Fisica Nucleare Sezione di Trieste

New silicon detectors



Gain CSA_1 = 100 CSA_2

FE electronics for the NCC: considerations

FE electronics requirements

↓

Is CR1.4P suitable?

↓

Possible alternative solution

INFN Istituto Nazionale di Fisica Nucleare Sezione di Trieste

FE electronics requirements

- Dynamics: 500 MIPs
- SNR: ~10 for 1-MIP signals
- Si detectors: *6x6* cm^2, *300 µm* thick, segmented in a *4x4* matrix of *1.5x1.5* cm^2 pixels
- Pixel capacitance: ~60 pF
- Readout rate: 10 MHz
- Readout channels: individual pixels, passive summation?
- Digitization: every clock or after LVL1 accept ?
- LL1 trigger: which kind of information from NCC ?

Is CR-1.4P suitable?

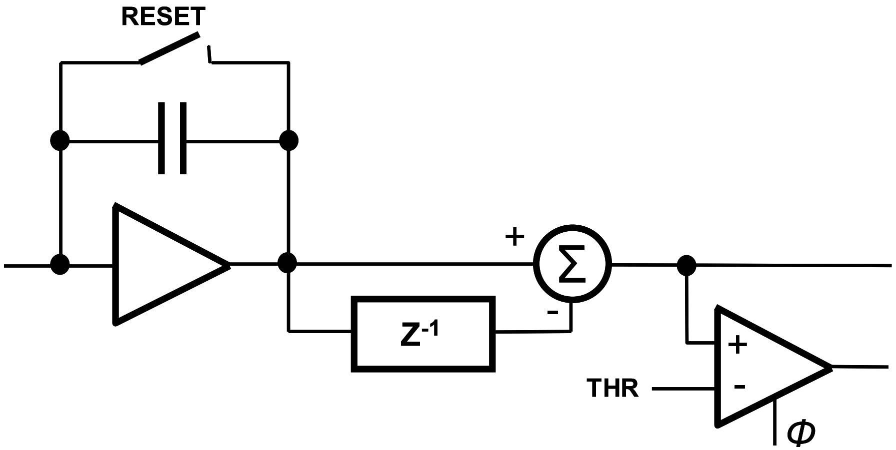
- Dynamics of 1400 MIPs is a bit too high, but gain is good for a 12 bit ADC with a range of 2.5V
- The outputs of the 16 channels are multiplexed
- Maximum rate of about 10 kHz (can be improved a bit at the cost of higher noise)
- Self-trigger system works only for large signals and requires a gating signal
- Pedestal dependence on temperature (1 MIP/°C) and on total input signal of the chip

NCC requires a new FE ASIC → a different architecture is strongly suggested

Possible alternative solution

Architecture of the proposed new FE ASIC (32 channels ?):

- Charge Sensitive Amplifiers with dynamic range of 2500 MIPs
- Correlated Double Sampling at RHIC clock, dynamic range of 500 MIPs
- Clocked comparator at the output for LL1 trigger system



- Reuse as much as possible what already exists: AMU/ADC32
- Alternatively, real-time digitization with external ADCs and digital memory
- If not enough space for the electronics near the calorimeter, consider the integration of 12 bit pipeline ADCs (one per channel)

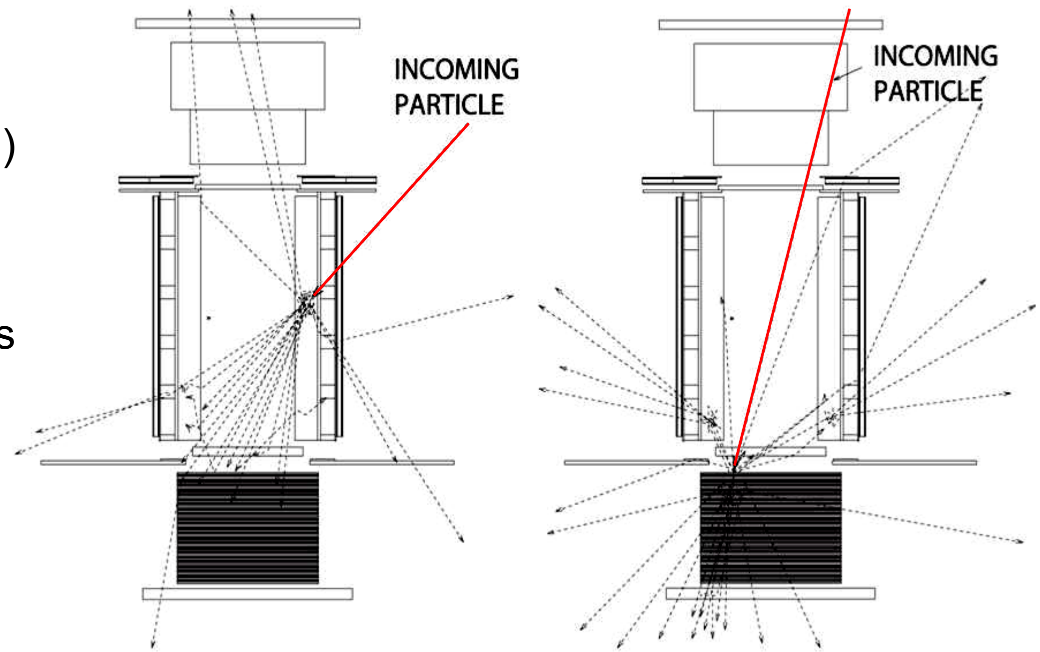
INFN Istituto Nazionale di Fisica Nucleare Sezione di Trieste

Extra slides
Results obtained with the calorimeter

INFN Istituto Nazionale di Fisica Nucleare Sezione di Trieste

Second level trigger

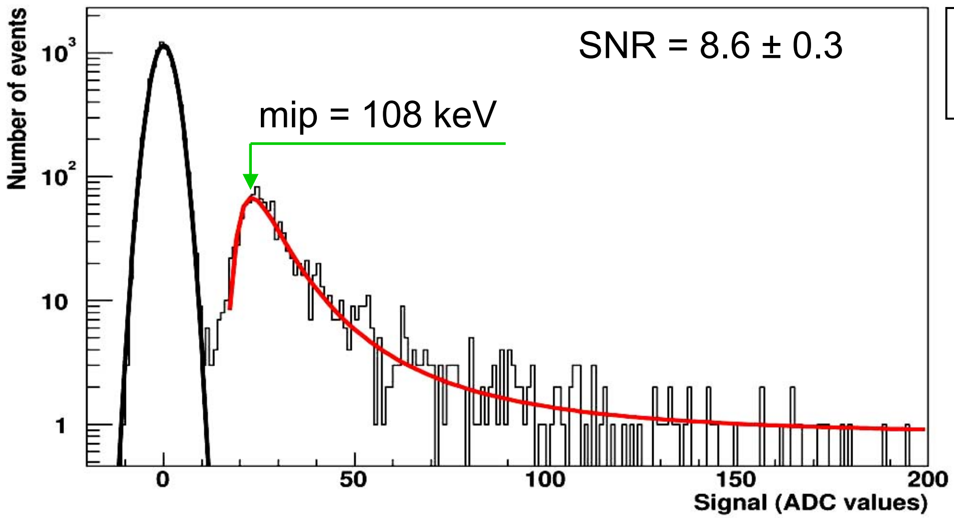
- Aim: use the anticoincidence (AC) signal to reduce the trigger rate
- Problem: backscattering of particles in the calorimeter



→ false trigger reduction ***70%*** at 95% of efficiency, estimated trigger rate of ***~5 Hz***

Calorimeter calibrations

- Conversion gain



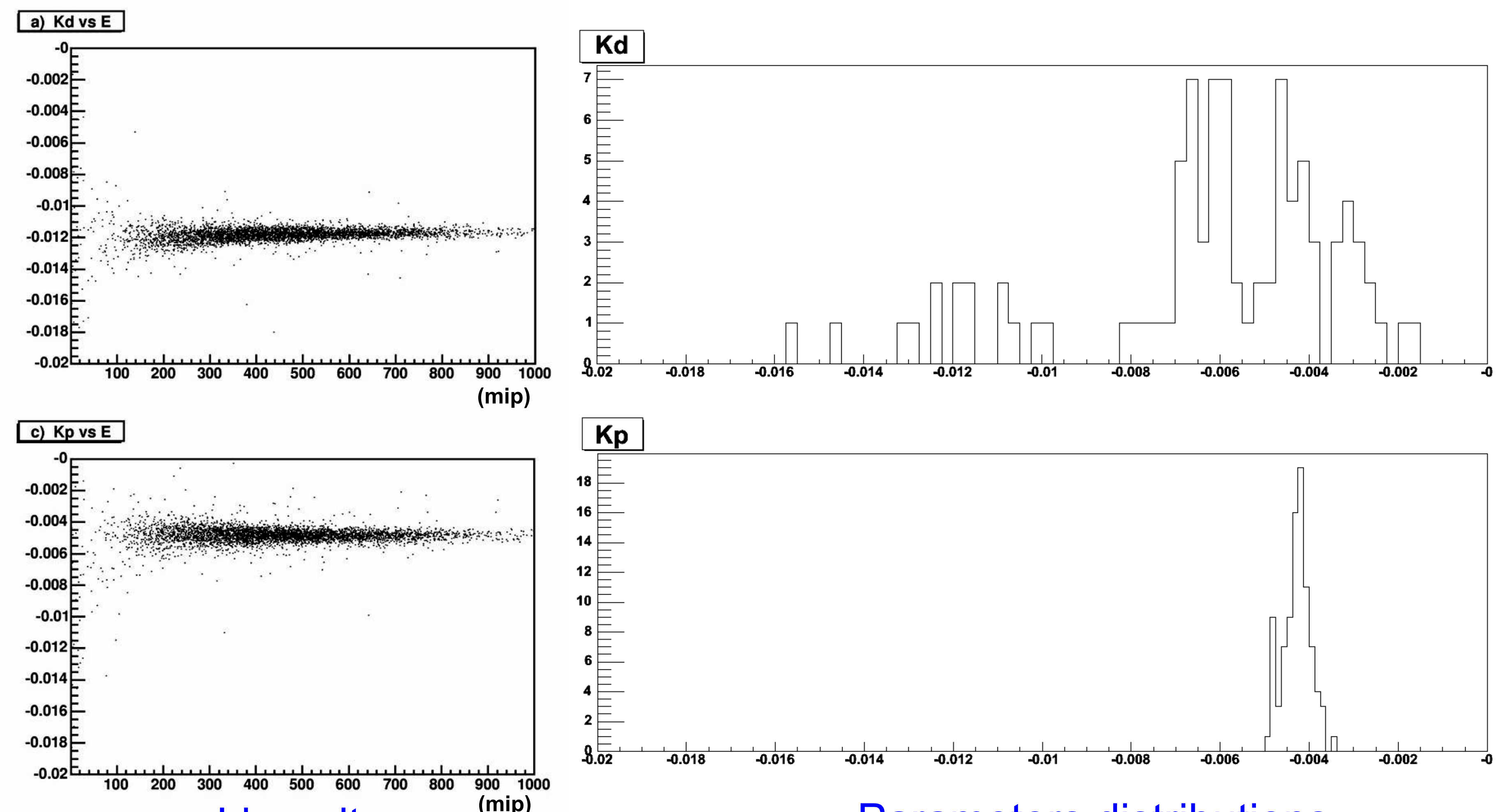
Test beam
50 GeV/c protons

- Baseline variations
  - detectors biased through a forward polarized p-n junction operating below threshold → high impedance toward the power supply → undesired injection in all strips through their junction capacitance
  - CR-1.4P: common bias of all shapers with poor output impedance→ change in the bias voltage → undesired signal in all channels

- Linear model:

$$\begin{cases} \Delta B_1 = K_D \cdot (E_1 + E_2) + K_P \cdot E_1 \\ \Delta B_2 = K_D \cdot (E_1 + E_2) + K_P \cdot E_2 \end{cases}$$

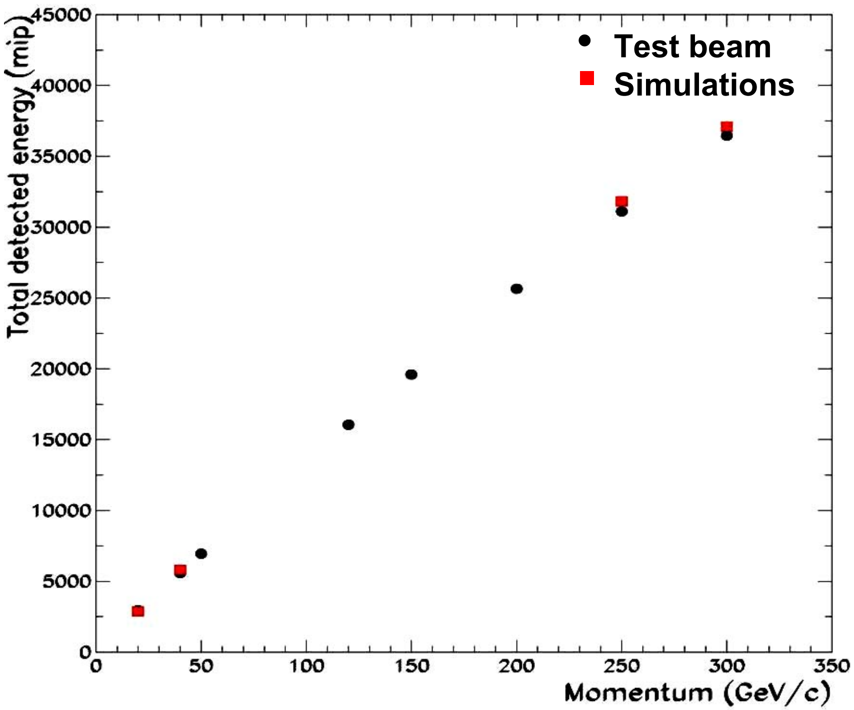
Baseline variations: model results

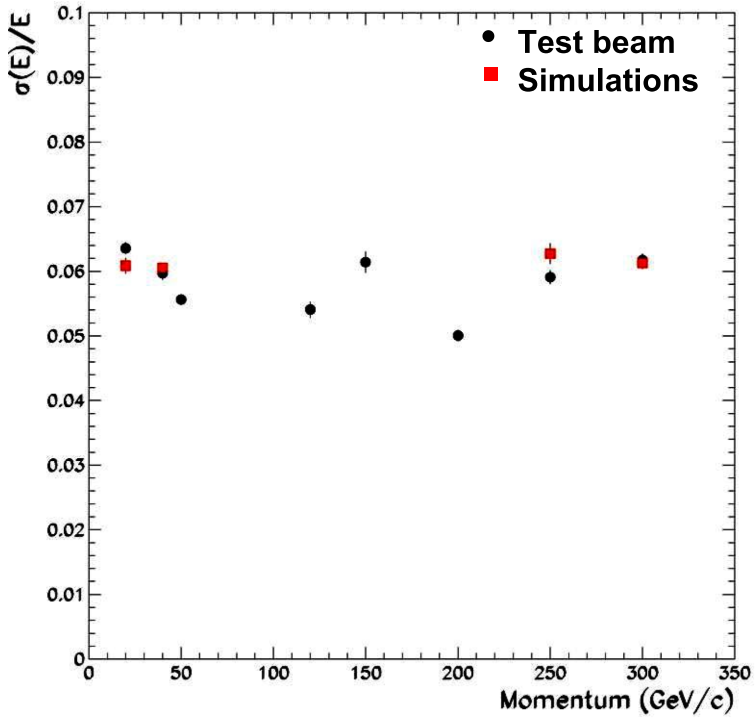


Linearity

Parameters distributions

Energy measurement



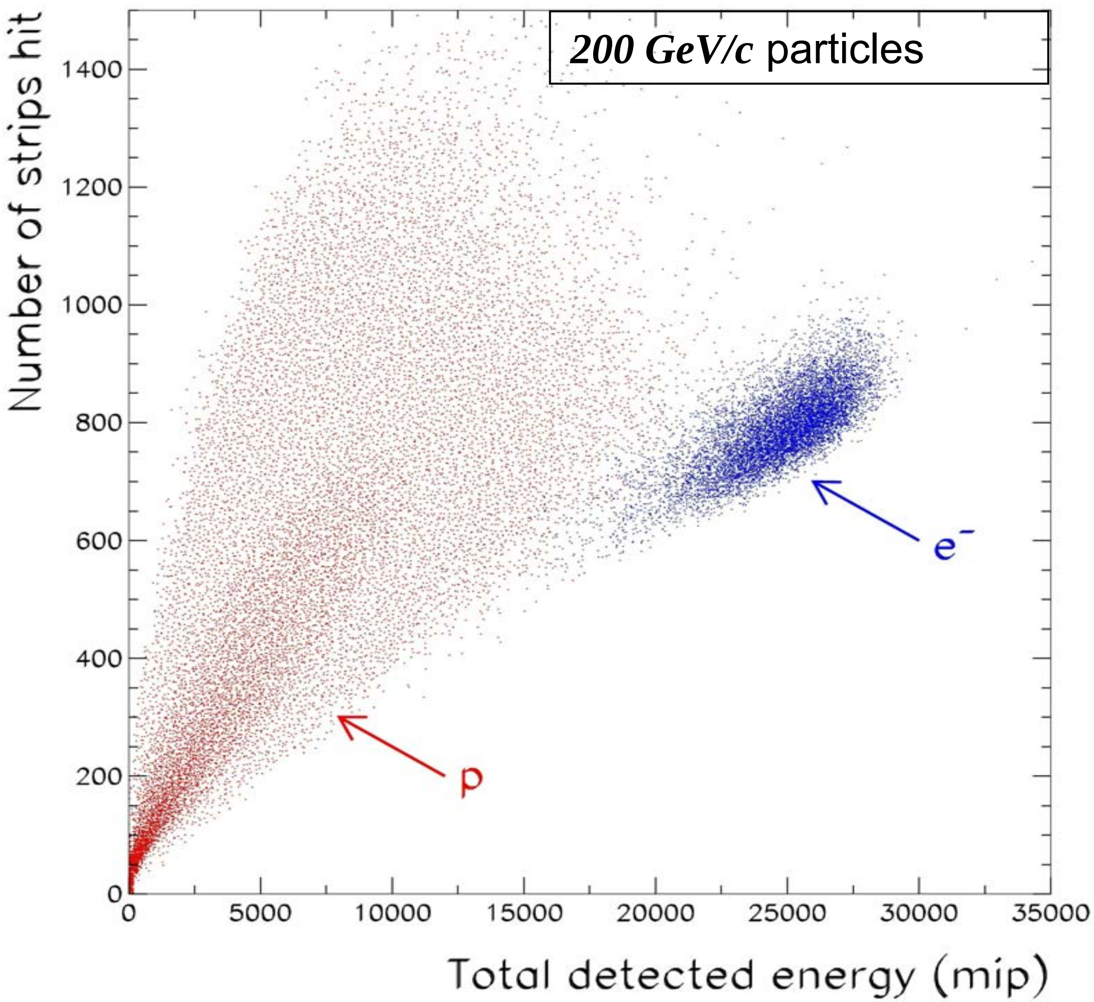


Data taken during test beam at CERN SPS, June 2002, with Calorimeter FM

- Test beam $\sigma_2=0.055$, simulations $\sigma_2=0.061$
- Expected resolution of the fully equipped calorimeter: ≤*5%* in this energy range

INFN Istituto Nazionale di Fisica Nucleare Sezione di Trieste

Particle identification



Data taken during test beam at CERN SPS, June 2002, with Calorimeter FM

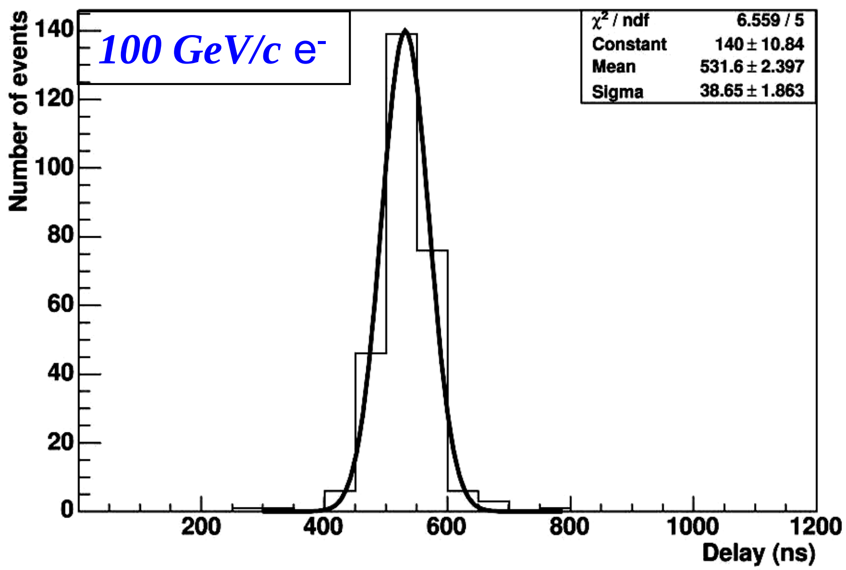
- Efficiency *95%*
- Rejection factor *$3 \cdot 10^4$*
  (8 protons out of 250000 misidentified as electrons)

INFN Istituto Nazionale di Fisica Nucleare Sezione di Trieste

Self-trigger system test

- Front-end trigger time response depends on signal amplitude → time coincidence to reduce delay spread (± *150 ns* is the max. allowed jitter for a sampling error < *1%*)
- Simulations to define system parameters:
  - Active trigger layers: from *4th* to *9th*
  - threshold = *150 mip*
  - Coincidence window = *90 ns*

  → trigger rate = *10 mHz*
- Self-trigger signals of the calorimeter sections logically OR-ed



particle	p [GeV/c]	measured efficiency	simulated efficiency
e^-	100	0.172 ± 0.004	0.236 ± 0.007
e^-	150	0.679 ± 0.008	0.986 ± 0.002
e^-	180	0.888 ± 0.005	0.990 ± 0.002
e^-	300	–	0.994 ± 0.007
p	100	$(2 \pm 1)\cdot 10^{-4}$	$(6.3 \pm 0.8)\cdot 10^{-3}$
p	150	$(1.3 \pm 0.2)\cdot 10^{-3}$	$(25 \pm 2)\cdot 10^{-3}$

- Delay@*100GeV/c* *530 ns*, asymptotic value *430 ns* → the signal sampling is accurate