Test beam results on the Proton Zero Degree Calorimeter for the ALICE experiment

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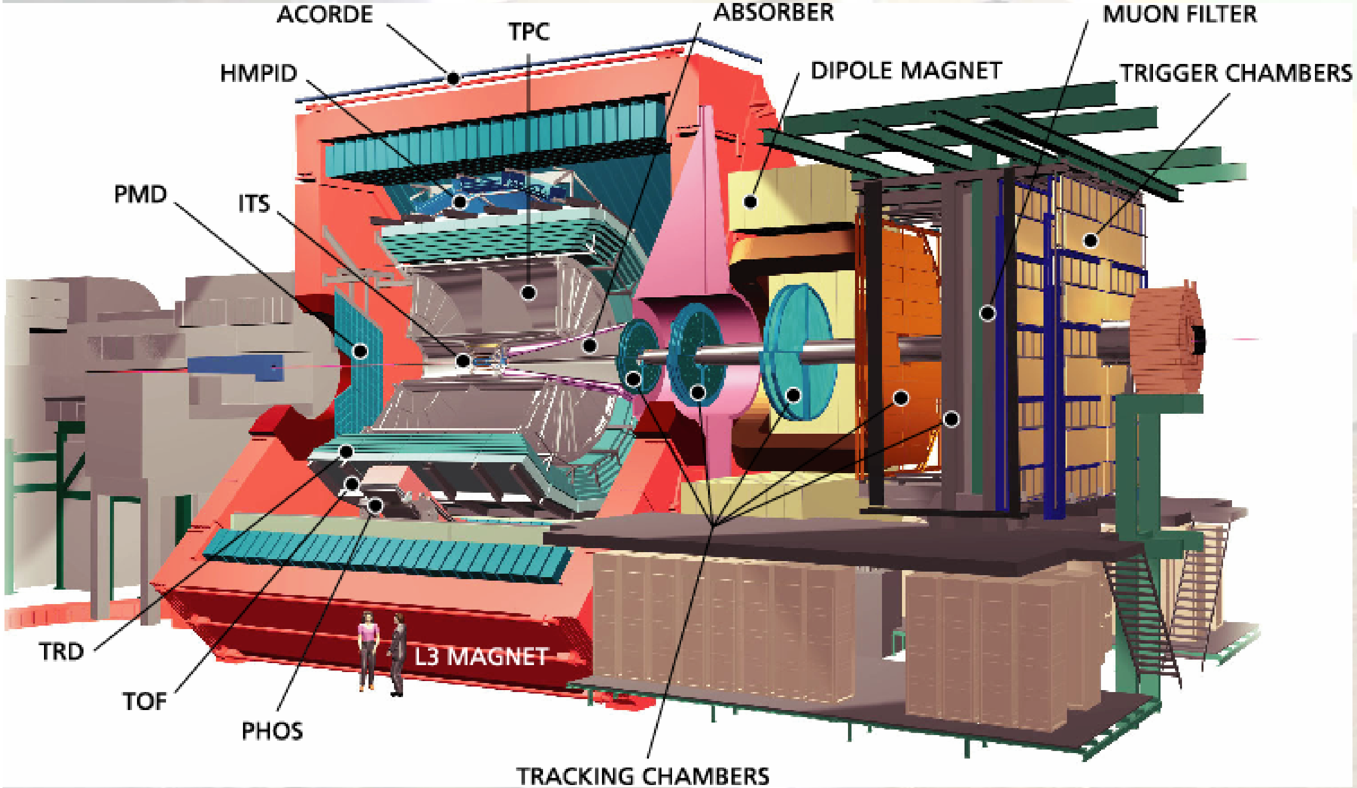
Outline

- **Zero Degree Calorimeters for the ALICE experiment**
- **Detection tecnique: quartz fibre calorimetry**
- **Description of the Proton Zero Degree Calorimeter (ZP)**
- **Test of ZP at the CERN SPS with hadron and electron beams**
- **Beam test results:**
  - **response to hadrons and electrons as a function of beam energy**
  - **e/π ratio**
  - **energy resolution versus the beam energy**
  - **uniformity of the response and fiber spacing**
  - **hadronic and electromagnetic visible shower lateral dimensions**
  - **p/π ratio**
- **Conclusions**

ALICE: the Heavy Ion experiment at LHC



Forward detectors ($\eta>4$) provide fast information about centrality in A-A interactions:

- FMD,T0,V0
- **ZDC ($\eta>8.7$)**

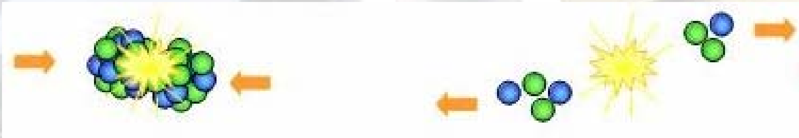
Study of hadronic signals, photons and dielectrons in a **Central Barrel** ($-1<\eta<1$)

Dimuon arm ($2.5<\eta<4$): study of muon pair production

Centrality measurement in H.I. experiment

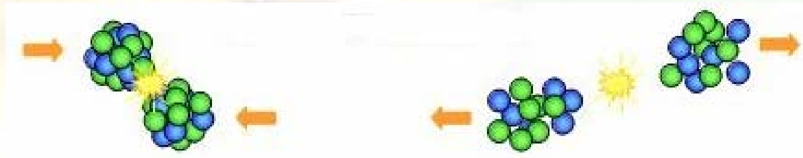
Many **QGP signatures** depend on **energy density**,
estimated through **centrality** of the collision

Central collision



Small impact parameter b
Large number of participants
High energy density
Small number of spectators
⇒ **Low energy in the ZDC**

Peripheral collision



Large impact parameter b
Small number of participants
Low energy density
large number of spectators
⇒ **Large energy in the ZDC**

Two identical sets of Zero Degree Calorimeters (**ZDC**), one on each side relative to the interaction point (I.P.), will measure the centrality of the collision through the detection of zero degree energy.

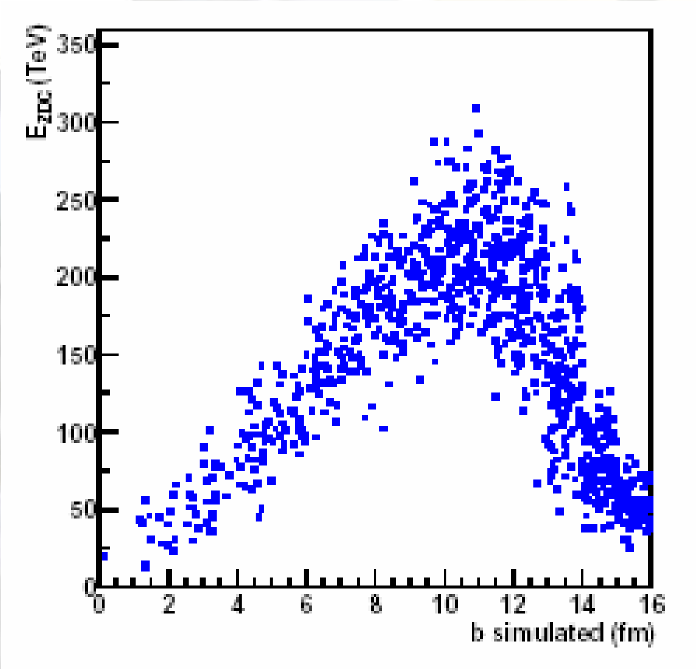
If **all** the spectator nucleons are detected, ZDCs allow a direct estimate of the number of interacting (participant) nucleons:

$$N_{part} = A - N_{spec} = A - E_{zdc} / E_A$$

where A is the mass number of the ion and E_A is the beam energy per nucleon.

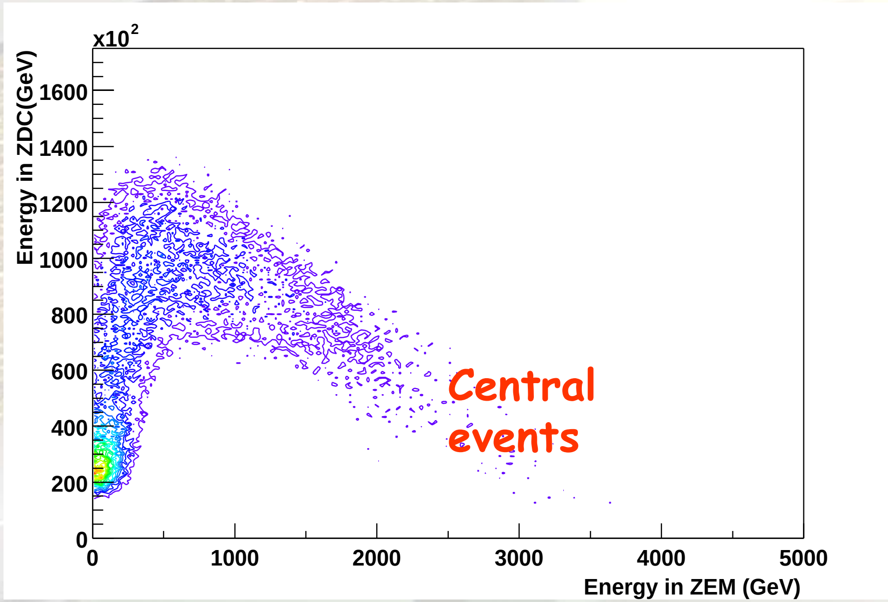
Centrality measurement at colliders

In H.I. collisions nuclear fragments are produced: at colliders they are lost in the beam pipes, owing to their magnetic rigidity, very close to the beam one.



In the **ALICE** experiment, considering fragments production, the monotonic correlation between E_{zdc} and the impact parameter b is still visible up to ~ 11 fm, but it is destroyed for very peripheral events.

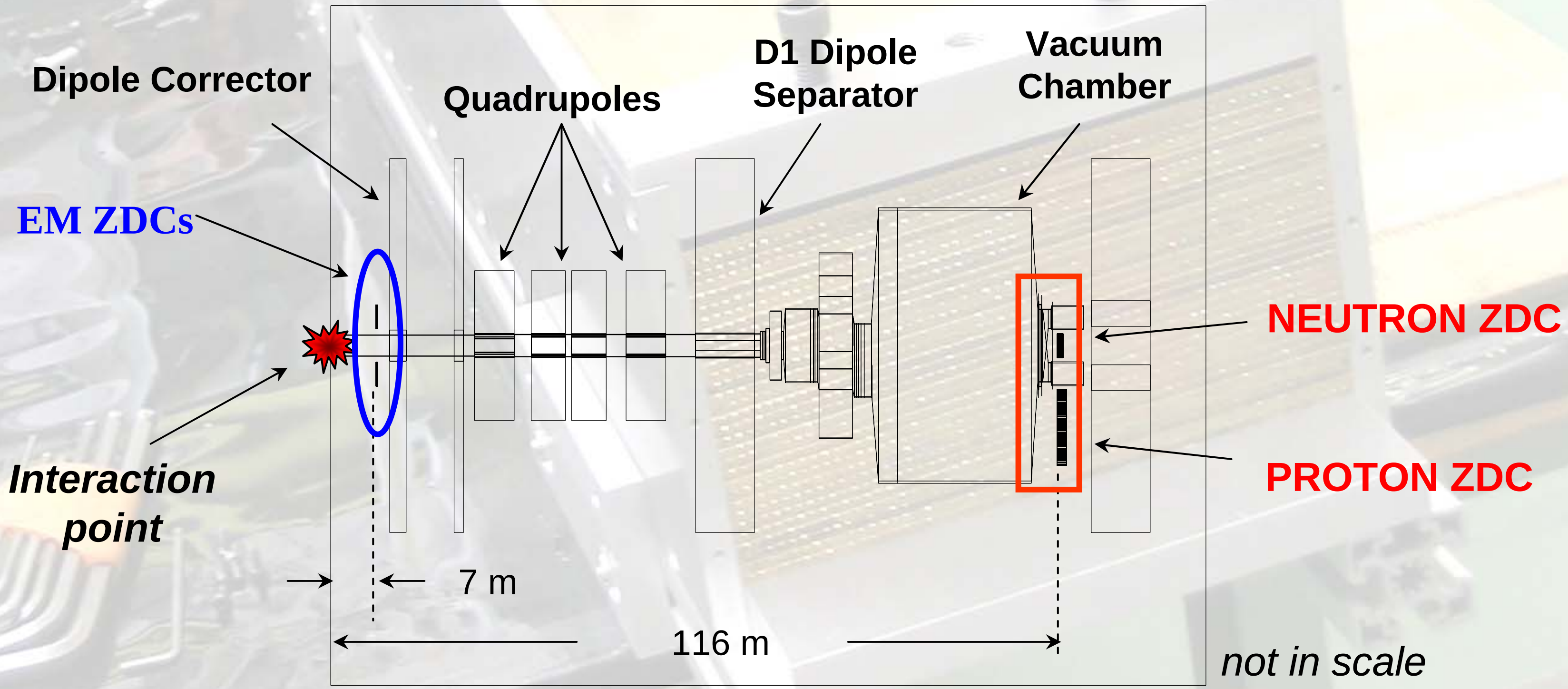
The information provided by two forward electromagnetic calorimeters (ZEM) will be used to identify very peripheral collisions and to remove the ambiguity



ZDCs for the ALICE experiment

The ZDC detector is made by

- two identical sets of hadronic “spaghetti” calorimeters, located at opposite sides with respect to the I.P., about 116 m away from it, where the beam pipes are separated. Each set consists of 2 calorimeters, 1 for spectator neutrons (ZN) and 1 for spectator protons (ZP), placed at **0°** with respect to LHC axis.
- two forward EM calorimeters placed at about 7 m from I.P., on the left side, covering the pseudorapidity range $4.8 < \eta < 5.7$.



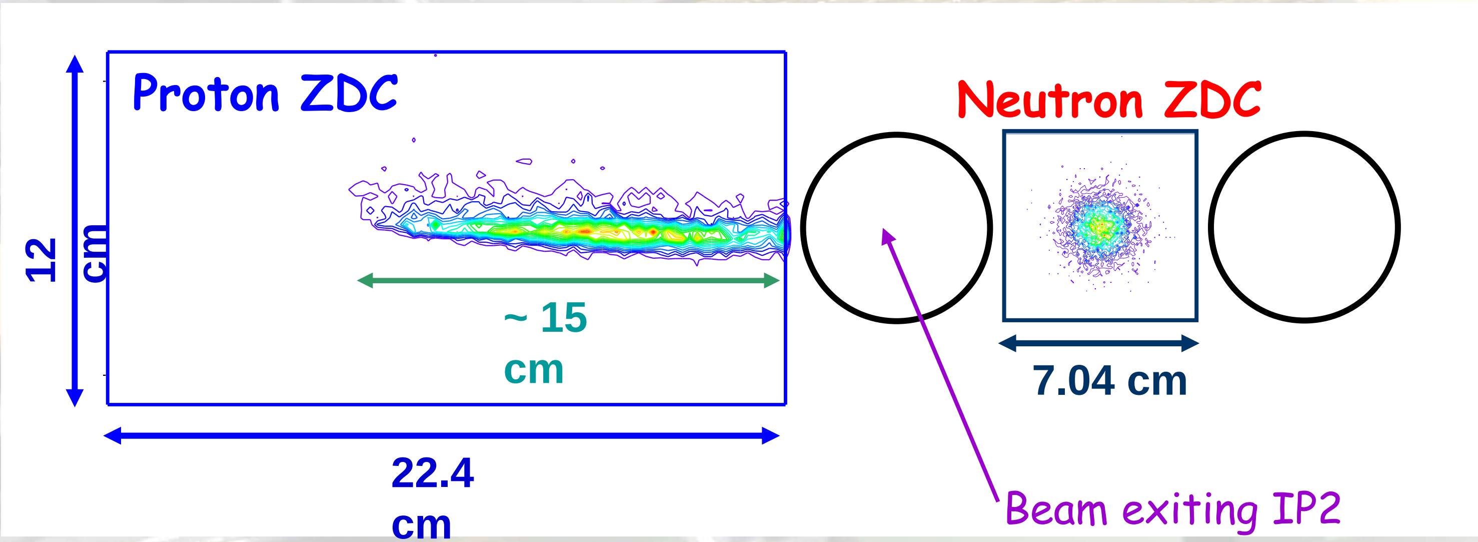
ZDCs' acceptances

Due to Fermi motion boosted by Lorentz transformations, **the spread for the longitudinal momentum of spectators**, is about 500 Gev/c.

The momentum spread of spectator protons results in a large horizontal dispersion after separator dipole D1, and some of them are lost along the beam line.

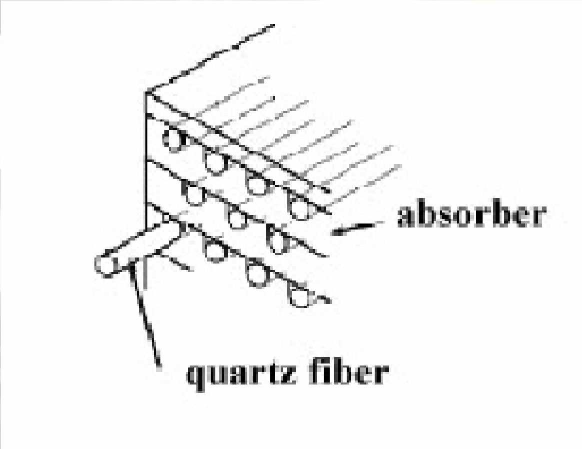
Spectator protons distribution over ZP front face is enlarged: 90% of detected protons hit a 12.6×2.8 cm^2 area.

For the spectator neutrons only the transverse component of the Fermi momentum plays a role in determining the size of the spot at the ZDC location, which is of the order of 0.6×0.6 cm^2 at 1 σ level. No losses of neutrons are expected along the beam line.



Detection technique

Quartz fiber calorimetry



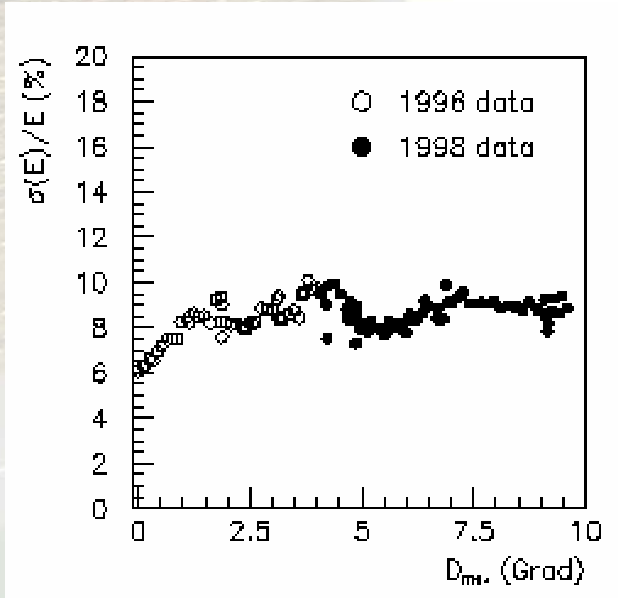
ZDCs are sampling calorimeters with silica optical fibers, as active material, embedded in a dense absorber.

The principle of operation is based on the detection of the Cherenkov light produced in the fibers by charged particles of the shower, induced by the spectator nucleons hitting the calorimeter front face.

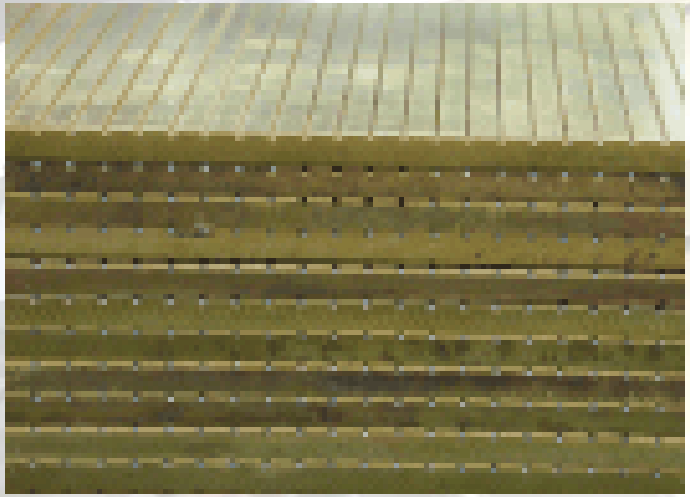
This technique fulfills various **ALICE requirements**:

- **reduced transverse size of the detectable shower ⟶ compact detectors**
- **signals' width < 10 ns ⟶ fast response**
- **high resistance to radiation**

good behavior of NA50 ZDC in an environment 10 times harsher than the ALICE one (R.Arnaldi et al. Nucl. Instr. and Meth. A(1998)1-6)



ZP for ALICE: detector description (I)



Passive material : brass

ρ = **9.0 g/cm³**

30 grooved slabs, each of them 4 mm thick, stacked to form a parallelepiped 22.4x12x150 cm³.

Active material : quartz fibers

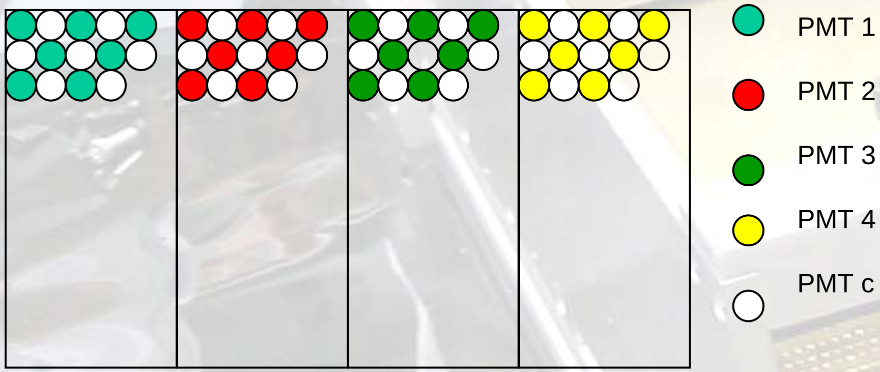
pure silica core, silica fluorinated cladding, and a hard polymer coat with a diameter of 550, 600, 630 μm respectively. The numerical aperture is 0.22

The active part of the detector is made of 1680 quartz fibers embedded in the absorber with a pitch of 4 mm, corresponding to a filling ratio, i.e. the ratio of active volume to the absorber volume, of 1/65.

The fibers are placed at 0° with respect to the beam axis and come out from the rear face of the calorimeter.

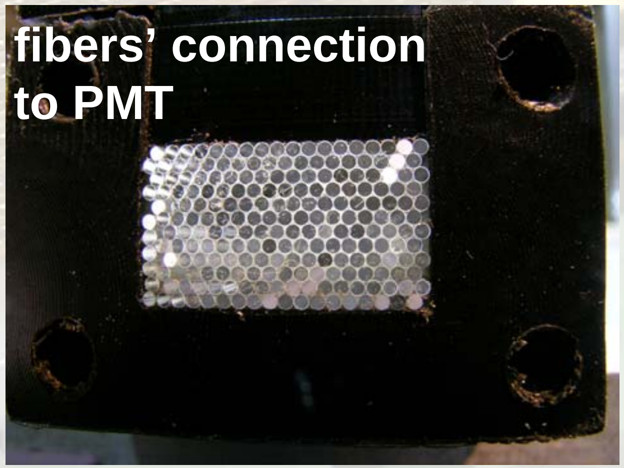
ZP for ALICE: detector description (II)

One every two fibers is sent to a single photodetector (PMTc), while the remaining fibers are connected to four different photodetectors (PMT1 to PMT4), collecting the light from four towers.



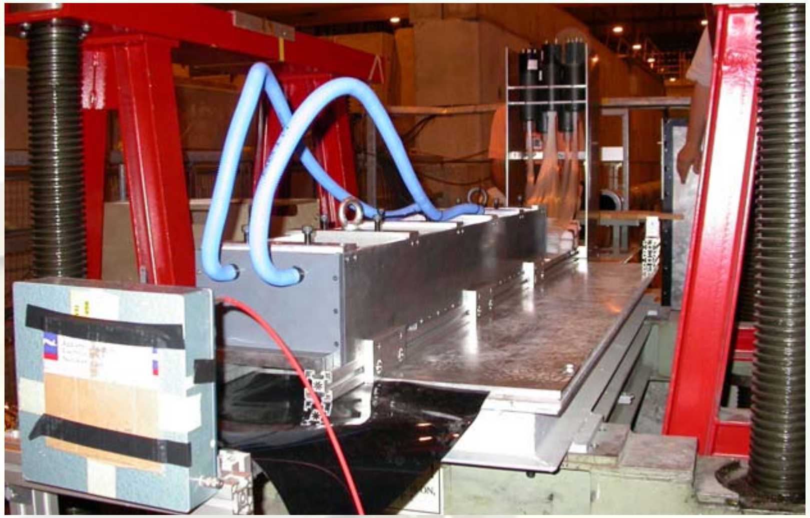
This segmentation allows:

- **to check the relative behaviour of the different towers**
- **to give a rough localisation of the spectator protons' spot.**



The 5 bunches of fibers are directly coupled with 5 PMTs Hamamatsu R329-02, with quantum efficiency around 25%.

ZP test at SPS: experimental set-up

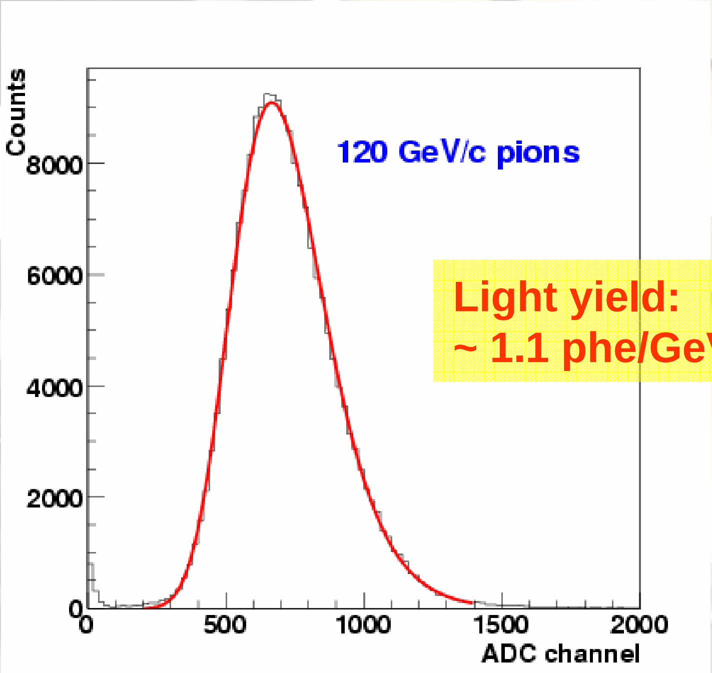


The first Proton ZDC was tested at H6 beam line of CERN SPS with :

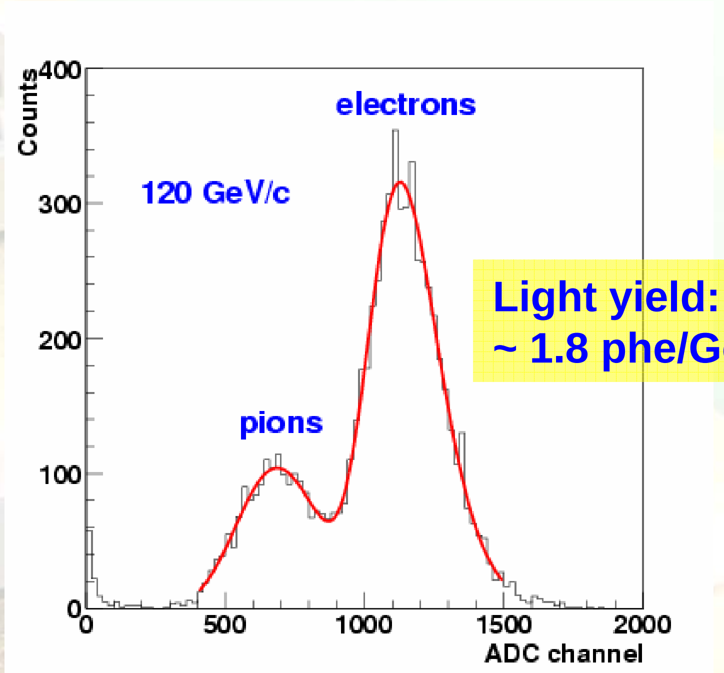
- **hadron beams (E = 50 ÷ 200 GeV)**
- **electron beams (E = 50 ÷ 180 GeV)**

- **S1**, **S2**, **S3**, **S4**: plastic scintillators to provide trigger
- **MWPC**: multiwire proportional chamber to ***define impact point*** on the calorimeter front face
- **MU1**, **MU2**: plastic scintillators to detect muons

ZP response to hadrons and electrons (I)



Light yield:
~ 1.1 phe/GeV



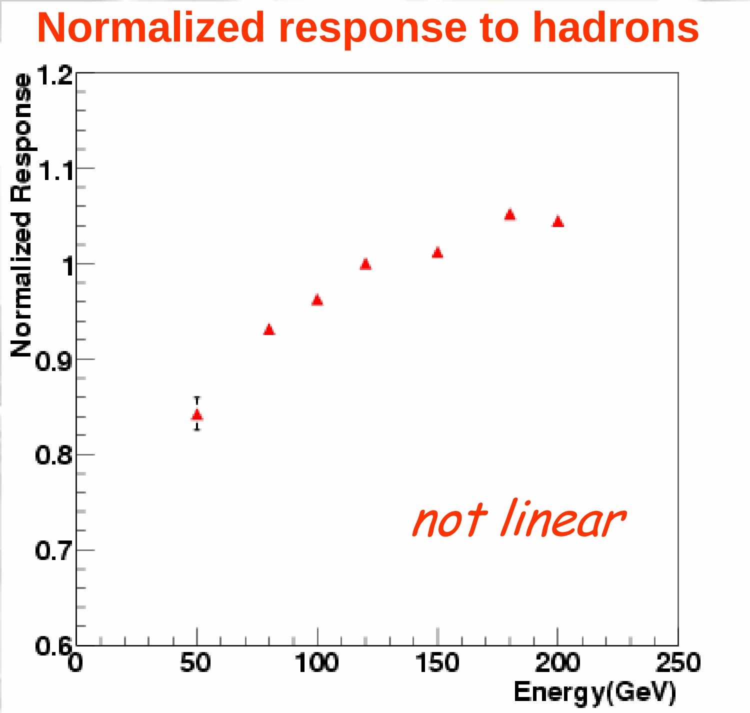
Light yield:
~ 1.8 phe/GeV

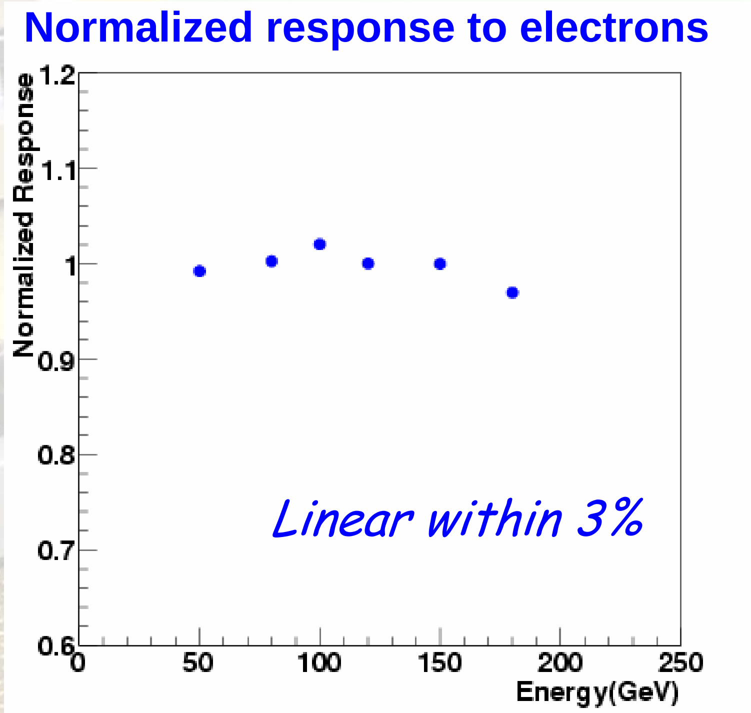
The non Gaussian shape of the calorimeter's response to hadrons is due to the energy fluctuations of the electromagnetic component of the hadronic shower.

The quartz fibers calorimeters are sensitive to this component, which arises from the π^0 produced in the initial interactions.

Fit to data: $f(x) = Ne^{-\frac{(x-\mu)^2}{2\sigma(x)^2}}$ where $\sigma(x) = \sigma_0 + \frac{\sigma_1(x-\mu)}{\mu}$

ZP response to hadrons and electrons (II)

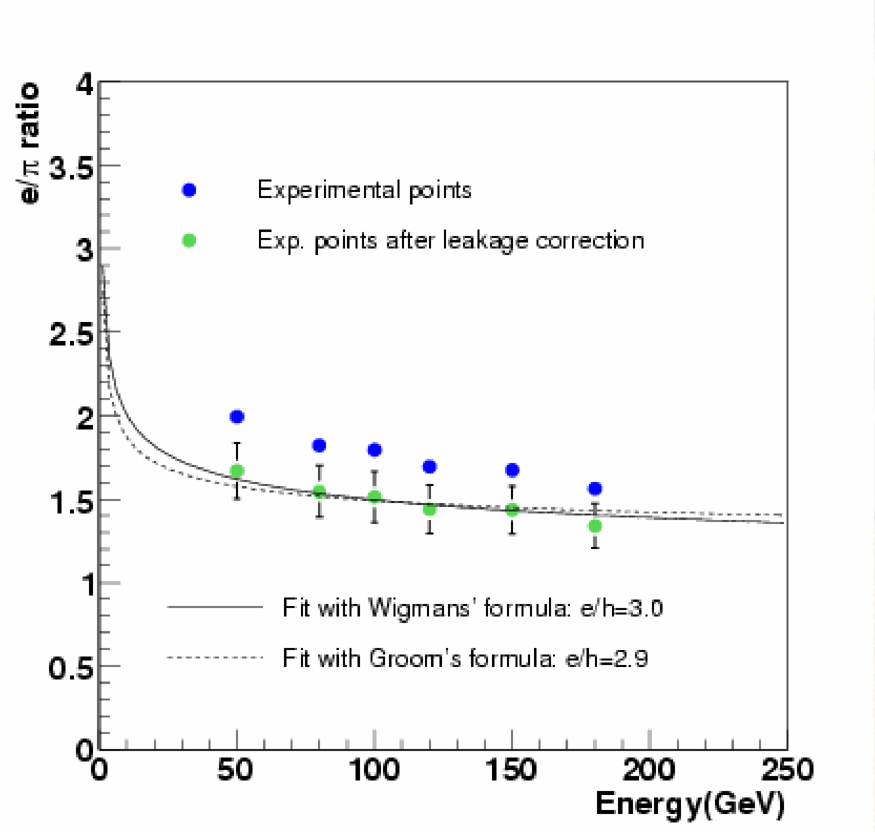




ZP is not compensating, **but in ALICE:**

- ✓ ZP measures the number of spectator protons, which have the same fixed energy as the beam nucleons.
- ✓ Charged particle produced at IP are bent by D1 separator magnet outside ZP.
- ✓ The energy due to the neutral particles hitting the calorimeter is found to be negligible compared to the energy carried by spectator protons.

e/π and e/h



e/h ≅ 3

The measured **e/π ratio** **has been corrected for the lateral leakage for π and fitted using**

$$\frac{e}{\pi} = \frac{\frac{e}{h}}{1-(1-\frac{e}{h})\, f_{\pi^0}(E)}$$

where f_{π^0} **is either Wigmans'**

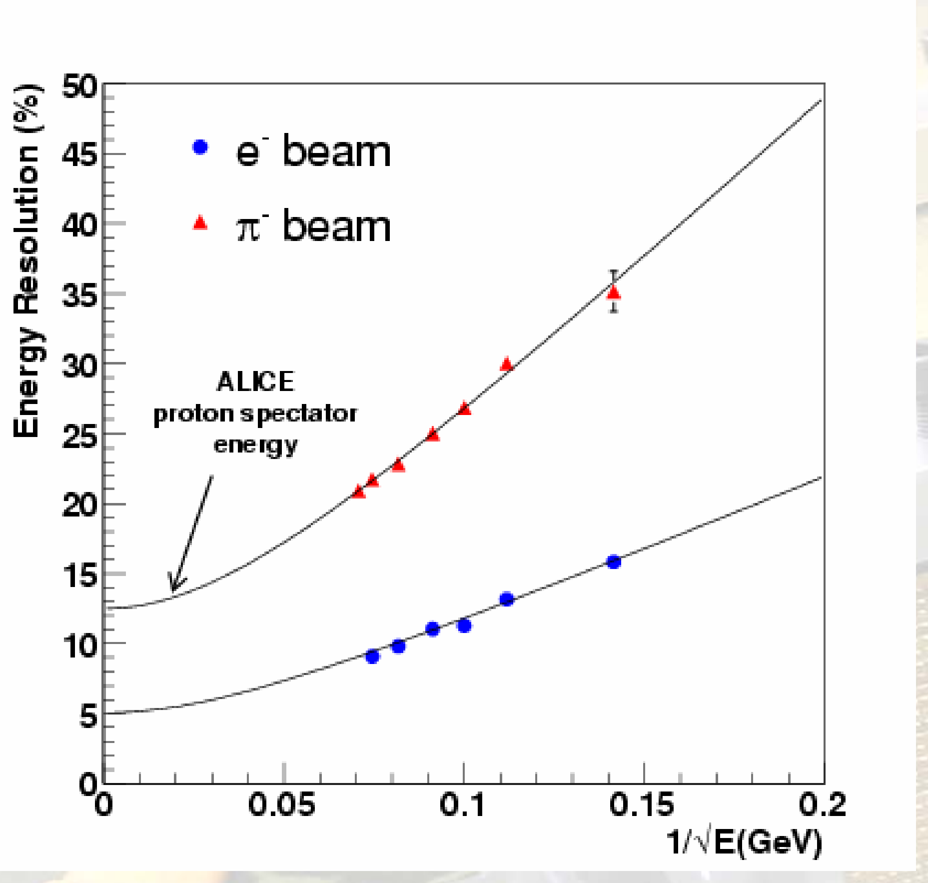
$$f_{\pi^0} = 0.11\log(E)$$

or Groom's

$$f_{\pi^0} = 1-(E/E_o)^{m-1}$$

and E_0 = 1 GeV **and** *m* = 0.85

Energy resolution



The black solid lines are the results of the fit:

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b$$

For electrons:

a = (106.8 ± 0.9) % GeV$^{1/2}$ b = (5.±0.3) %

For pions:

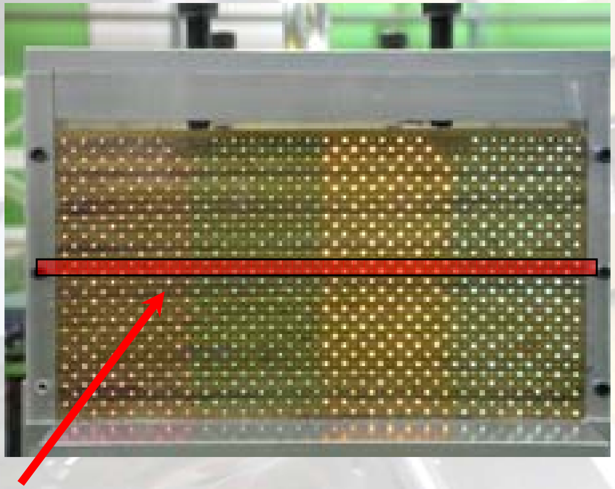
a = (237. ± 2.) % GeV$^{1/2}$ b = (12.5±0.2) %

Extrapolation to the ALICE proton spectator energy (**2.7 TeV**):

$$\frac{\sigma(E)}{E} \approx 13\%$$

ALICE ZDC should have an energy resolution comparable with the intrinsic fluctuations on the spectator nucleons, ranging from ≈ 20 % for central events to ≈ 5 % for peripheral ones.

Uniformity of the response (I)

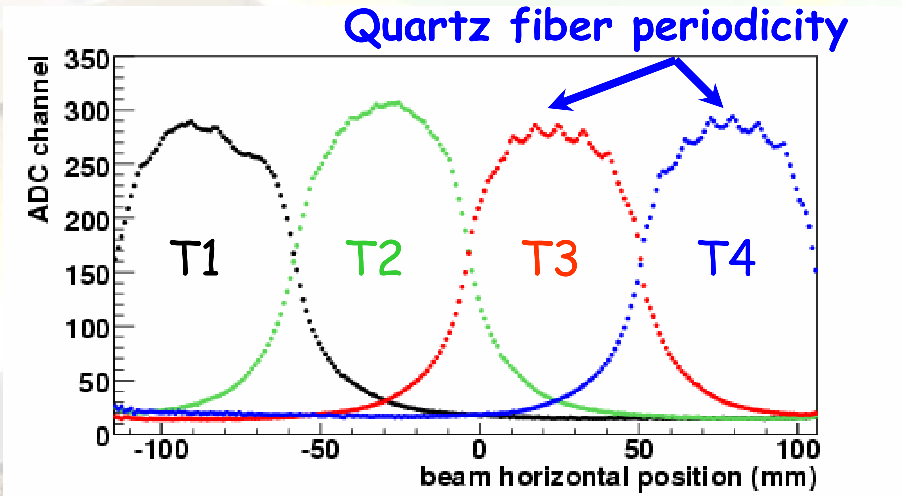


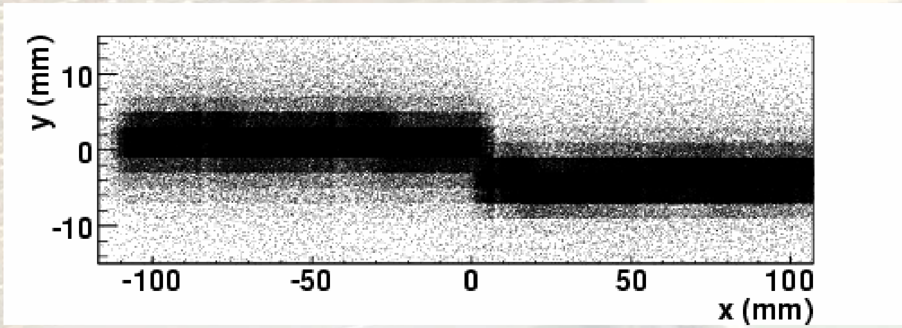
Scanning of calorimeter's front face with a 120 GeV/c pion beam

The responses of adjacent towers change as the beam moves from one tower to another.

The sampling fraction is slightly higher when the beam particles enter the detector in a fibre plane than when they enter in the absorber. For this reason the calorimeter is sensitive to the beam vertical position detected also by the MWPC.

Signals of four towers as a function of the beam impact horizontal coordinate



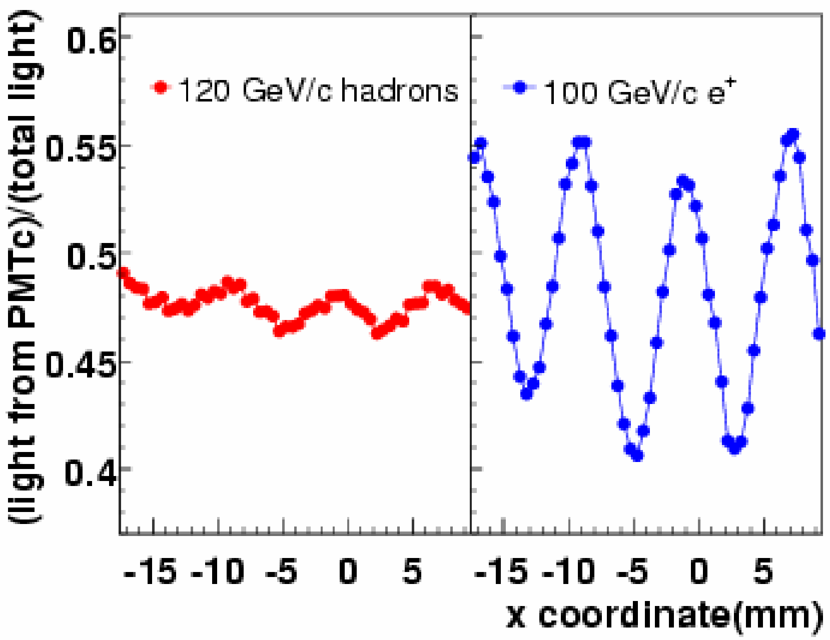


Beam impact point on the calorimeter front face defined using the MWPC

Uniformity of the response (II)

Fraction of light seen by the PMTc versus the horizontal coordinate of the beam impact point.

- **The plot refers to events within a thin window centered on a single fiber plane**
- **The periodicity of the fibers going to the same PMT (8 mm) can be seen**



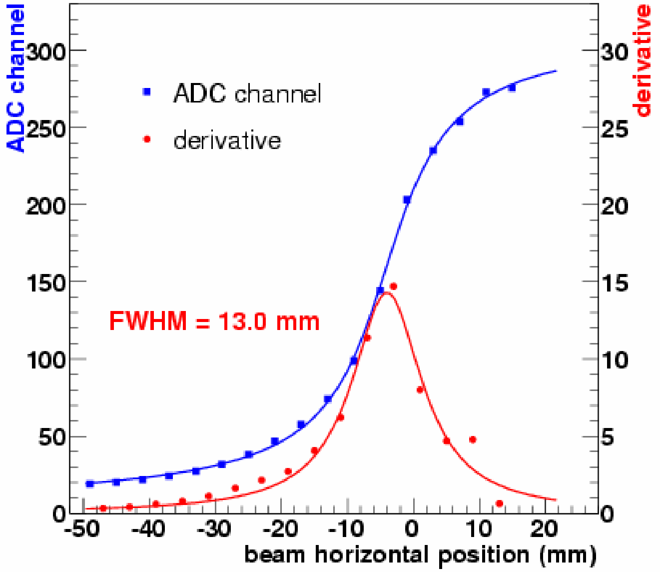
Clear oscillations (~15%) for the positrons beam are due to the size of the electromagnetic shower, strongly peaked near its axis.

Less important variations (~2.5%) for pion beam induced signals show that the ZP fiber spacing is adequate for *hadronic* calorimetry, as required by ALICE experiment.

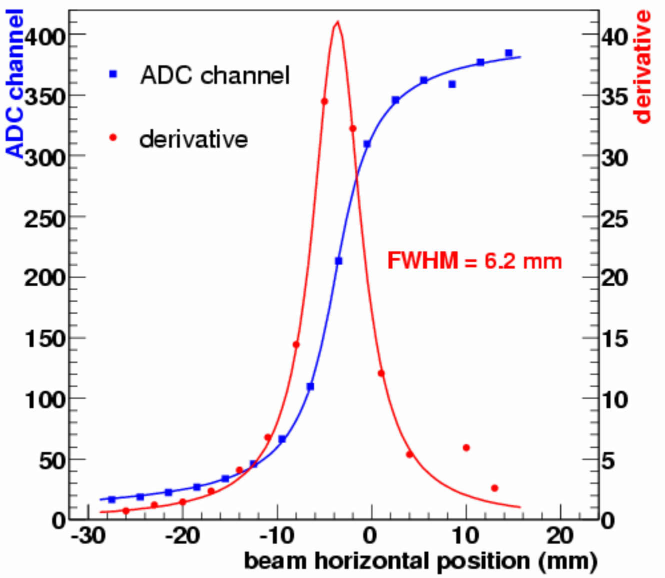
Detectable shower's transverse profile

The ZP is mainly sensitive to the central part of the shower, thanks to its principle of operation based on the detection of Cherenkov light.
The beam scan on the boundary region between two towers allows an estimate of the transverse size of the detectable shower.

120 GeV hadron beam scan



100 GeV positron beam scan



- **Response of a single ZP tower (T3) as a function of the beam impact point on the front face of the calorimeter**

Experimental data have been fitted with an arctangent function

- The derivative of the data shows, for the **shower's transverse profile, a FWHM** of:
  - ~ **13 mm** for **hadrons**
  - ~ **6 mm** for **e+**

Difference in responses to p and π (I)

spectra analysis

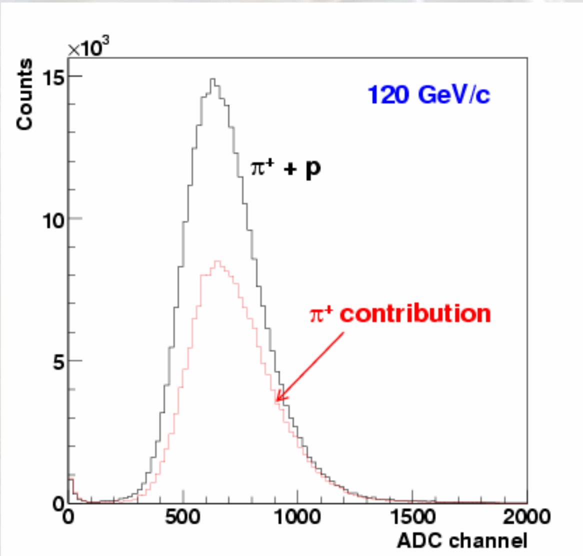
For three beam momenta the calorimeter behaviour has been investigated with both negative and positive hadron secondary beams.

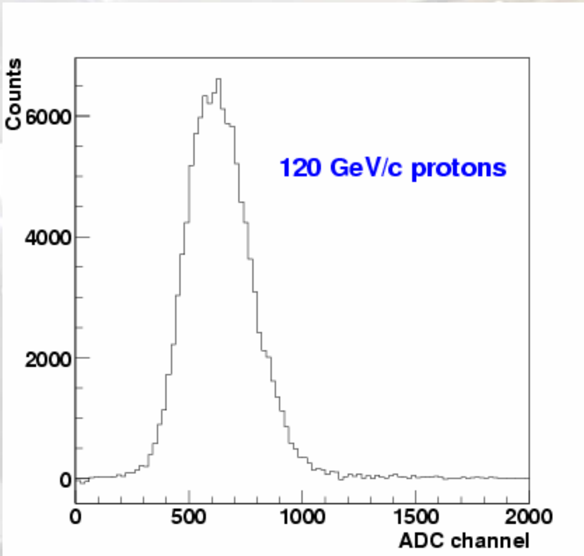
Negative beams are composed almost entirely by pions.

Positive beams are a mixture of pions and protons.

CERN SPS data

Beam momentum	Production angle (mrad)	Fraction of pions
100 GeV/c	-5.46	61%
120 GeV/c	-0.2	61%
150 GeV/c	5.	31%





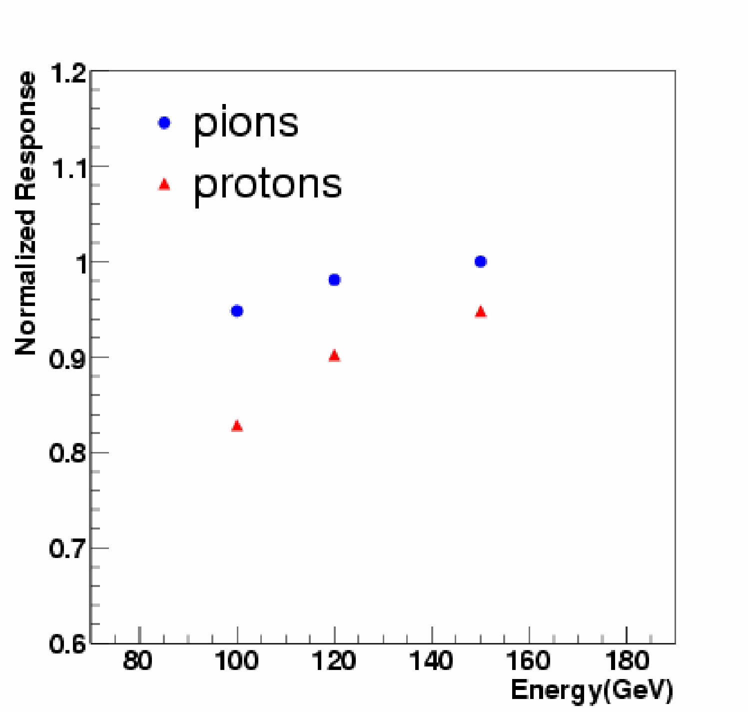
It is possible to separate π^+ and proton contributions to positive beam spectra because:

- **the fraction of pions is known**
- **the shape of π^+ spectra is assumed to be equal to π^- spectra's one**

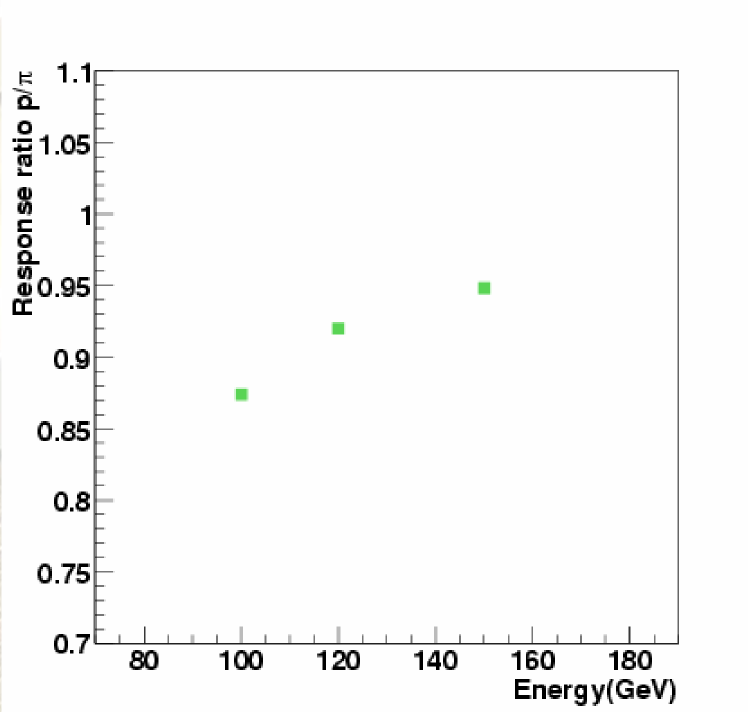
Difference in responses to p and π (II)

p/π ratio

Normalized response to pions and protons



p/π ratio as a function of beam energy

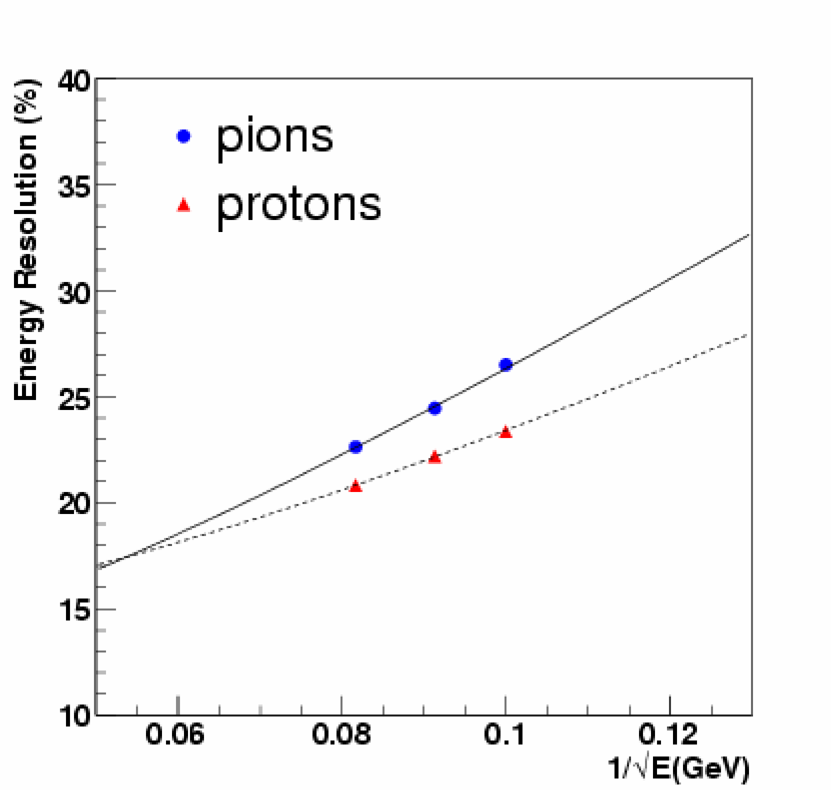


ZP response to protons is, on average, ~ 8.5 % lower than the response to pions of the same energy, due to:

- **proton interactions have a smaller fraction of energy going into π^0's than pion interactions**
- **ZP is non-compensating**

Difference in responses to p and π (III)

energy resolution



The black solid lines are the results of the fit:

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b$$

For pions:

a = (234. ± 5.) % $GeV^{1/2}$ b = (12.1±0.7) %

For protons:

a = (185. ± 4.) % $GeV^{1/2}$ b = (14.3±0.4) %

The energy resolution for protons is better than for pions, despite the fact that ZP response to protons is lower than the response to pions.

Conclusions

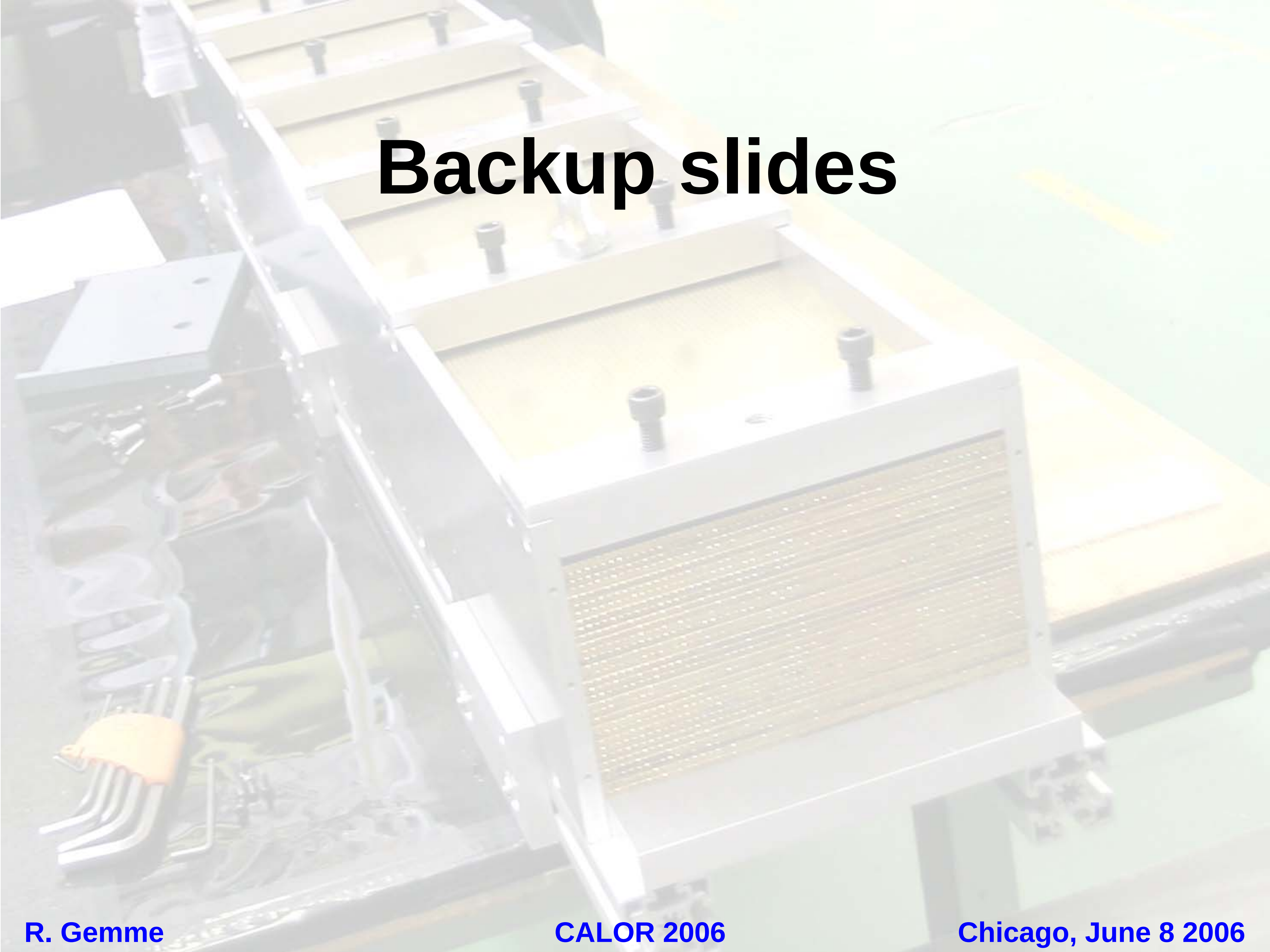
The first proton ZDC for the ALICE experiment has been tested with hadrons and electrons beam at CERN SPS.

Results of the test show that:

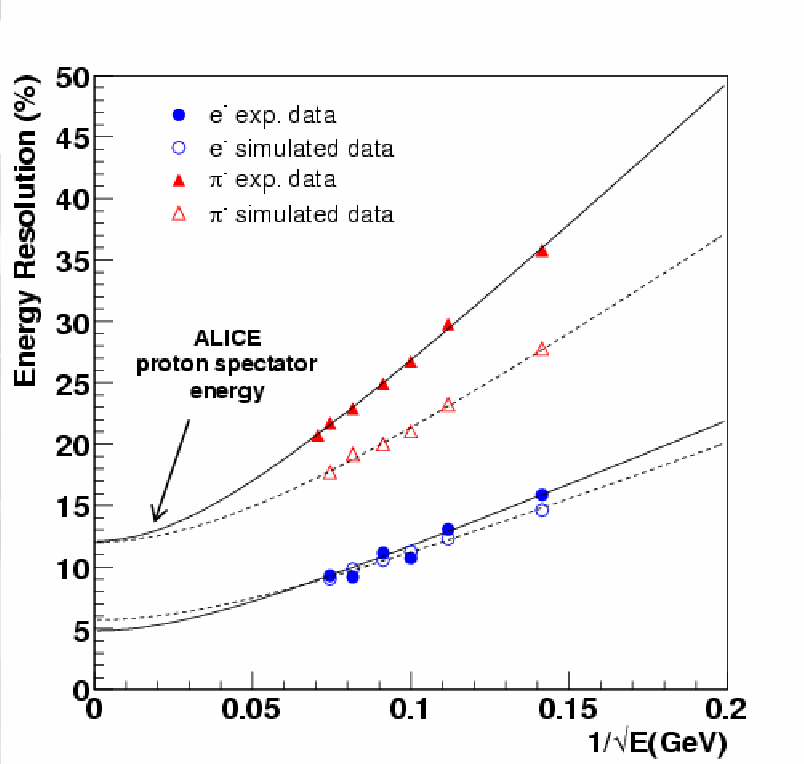
- **ZP has a linear response to electrons in the energy range from 50 to 180 GeV**
- **The calorimeter is non-compensating, the e/h value is ~ 3 (but this won't create any problem in the ALICE experiment)**
- **Energy resolution extrapolated to the energy of the single spectator nucleon in ALICE (2.7 TeV) is ~ 13%**
- **Sampling frequency adequate for hadronic calorimetry**
- **The calorimeter shows a detectable transverse size of ~ 6 mm FWHM for electromagnetic showers and ~ 13 mm FWHM for hadronic showers**
- **The detector is sensitive to the different electromagnetic component of the hadronic showers developed by pions and protons**

ZP fulfill the requirements of the ALICE experiment for the determination of event centrality

Backup slides



Energy resolution: comparison with simulation



A GEANT 3.21 simulation of the ZP test beam has been performed.
The plot shows a good agreament between simulated and experimental data for electrons.

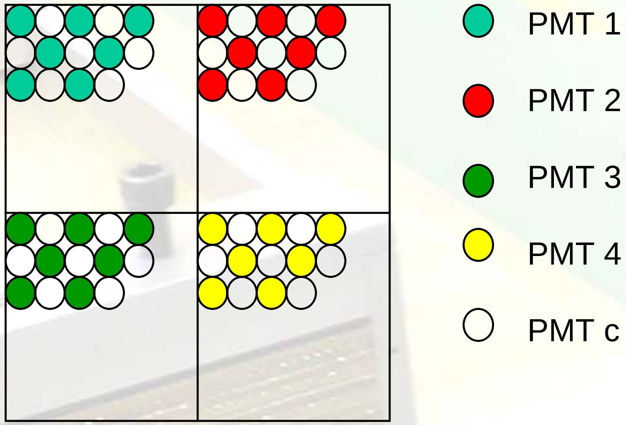
Both simulated and experimental points have been fitted with:

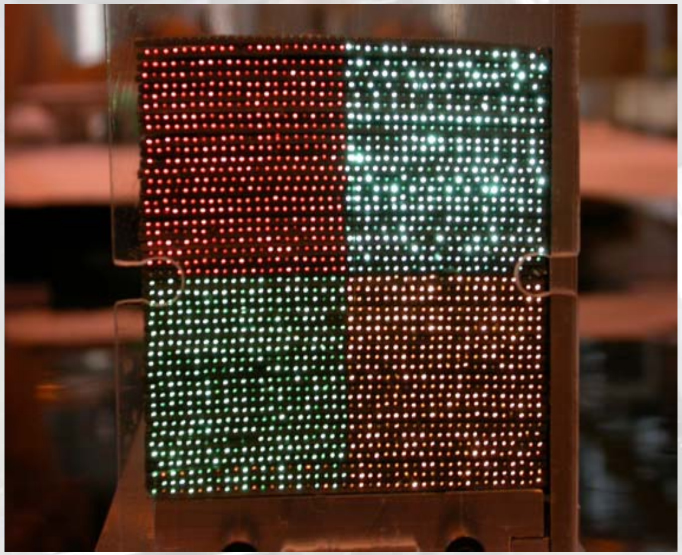
$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus b$$

ALICE ZDC should have an energy resolution comparable with the intrinsic fluctuations on the spectator nucleons, ranging from ≈ 20 % for central events to ≈ 5 % for peripheral ones.

ZN as rough position sensitive device

One out of two fiber is sent to a photomultiplier (PMTc), while the remaining fibers are collected in bundles and sent to four different photomultipliers (PMT1 to PMT4) forming four indipendent towers.





This segmentation gives a rough localization of the spectator neutron’s spot on the front face of the calorimeter.

Reconstruction of the centroid of the spectator neutrons spot

The **centroid** **of the spectator neutrons spot on the ZN front-face is estimated by means of the relations:**

$$x = const \cdot \frac{\sum_{1}^{4} x_i^t w_i}{\sum_{1}^{4} w_i} \qquad y = const \cdot \frac{\sum_{1}^{4} y_i^t w_i}{\sum_{1}^{4} w_i} \qquad w_i = E_i^{\alpha}$$

where x_i^t and y_i^t are the coordinates of the centre of the i-th tower and E_i is the light in the i-th tower.

α and **const** are free parameters introduced in order to get an accurate reconstructed impact coordinate.