Development of an Hadronic Tile Calorimeter for TESLA

E. Garutti (for DESY-HCAL group)

- New calorimeter concept for linear collider detector
- The analogue hadronic calorimeter for TESLA
- Detector R&D:
  - -Tile-fiber system
  - - Fiber coupling to photo-detector
  - - Photo-detectors options
    - ➔ Avalanche Photo-Diode (Hamamatsu)
    - ➔ Silicon Photo-Multiplier (MEPHI, PULSAR)

- Results from first prototype ➔ establish new technologies
- Preparation of physics prototype ➔ physics studies

Physics Motivation

From the 4th ECFA workshop (Jean Claude Brient):

Di-jet mass resolution, lepton tagging in jet environment,etc…

<u>Shower to shower separability</u>

- separation charged hadrons/photon and charged hadrons/neutral hadrons

  Give access to the best possible Ejet and di-jet mass resolution

<u>Lepton identification in jet</u>

- electron, mu and tau tagging in jet

  Identification of jet flavor, W vs Z, etc

<u>Needed to see a signal at 5σ</u>

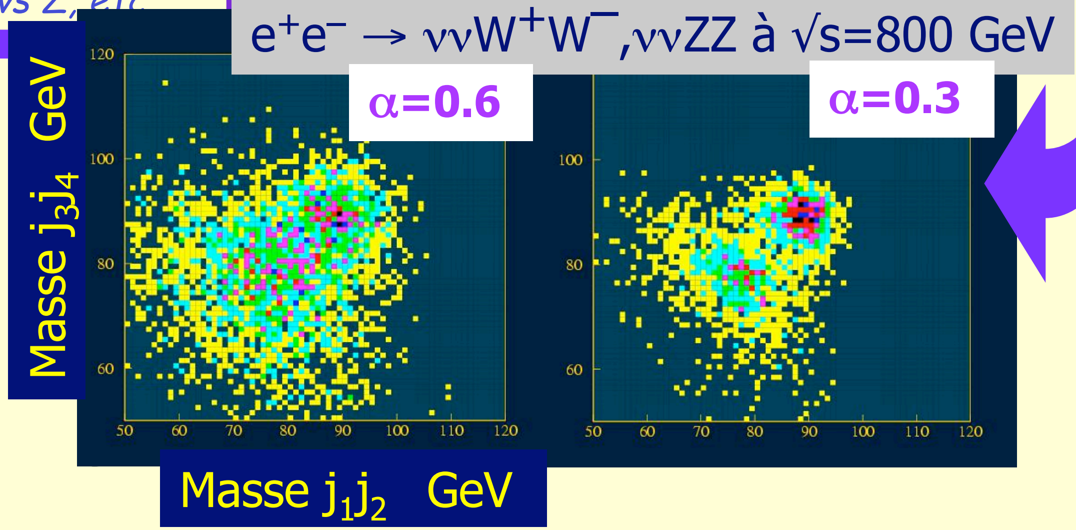
- Higgs self-coupling and ?? ttH ,…??

<u>Dependence on the measurement precision</u>

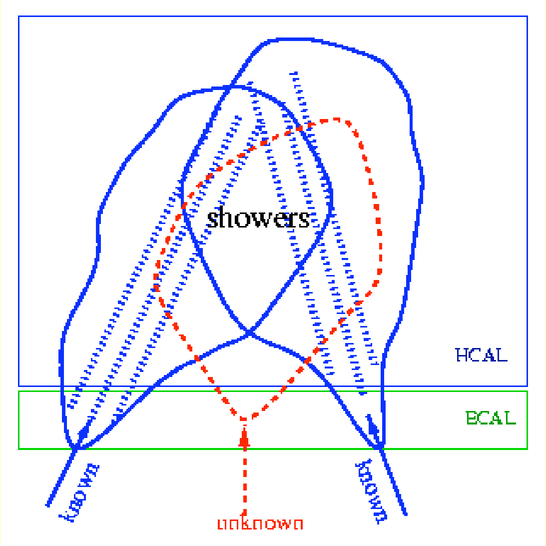
- Higgs BR in WW
- W_L coupling ($\nu\nu W^+W^-$ versus $\nu\nu ZZ$)

Total segmentation and high granularity is mandatory !!!

$e^+e^- \rightarrow \nu\nu W^+W^-, \nu\nu ZZ$ à $\sqrt{s}$=800 GeV



Particle Flow Algorithm



Based on two ideas:

-TPC momentum resolution higher than calorimeter energy resolution

-Vector subtraction from overlapping showers is more effective than scalar subtraction

Particle flow concept:

- for all charged particles merge TPC track to calorimeter clusters
- substitute calorimeter energy with momentum
- the rest of energy is assigned to neutral clusters, divided into:
    - gammas (ECAL)
    - neutral hadrons (HCAL)

➔Such a technique requires high granularity of both ECAL and HCAL

The CALICE Collaboration

CAloremeter for the LInear Collider with Electrons

168 physicists from 28 institutes and 8 countries

Coming from the 3 regions (America, Asia and Europe)

ECAL project:

- 40 layers of W-Si sandwich with pads of 1x1 cm^2 ➔ TRACKER CALORIMETER

energy resolution on electron/photon ~ $\Delta E/E = 11\% / sqrt(E)$

- other options are also possible

HCAL project:

Solution 1) Tile HCAL

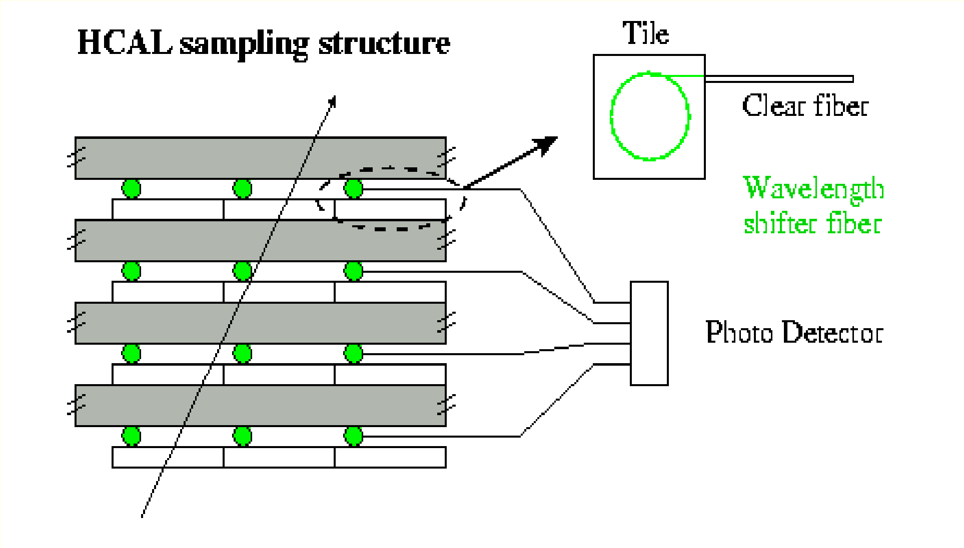
3x3 to 12x12 cm^2 tiles with analogue readout

➔Developed at DESY ← see the rest of the talk

Solution 2) Digital HCAL

A tracker calorimeter with 1x1 cm^2 pads and 40 layers with digital readout

Tile HCAL



Sampling structure:

20mm Fe + 5mm Scintillator

(~ 1.15 X_0 or 0.12 λ)

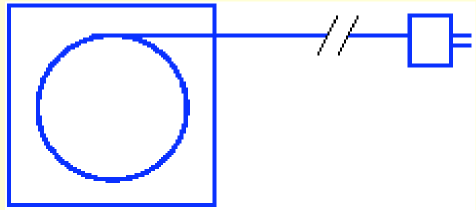
Tile readout:

Wave-Length Shifter fibers

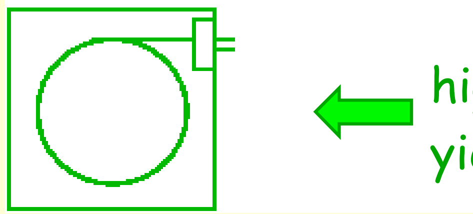
+ Photo-detector

→ Two possibility:

"conventional"



direct coupling



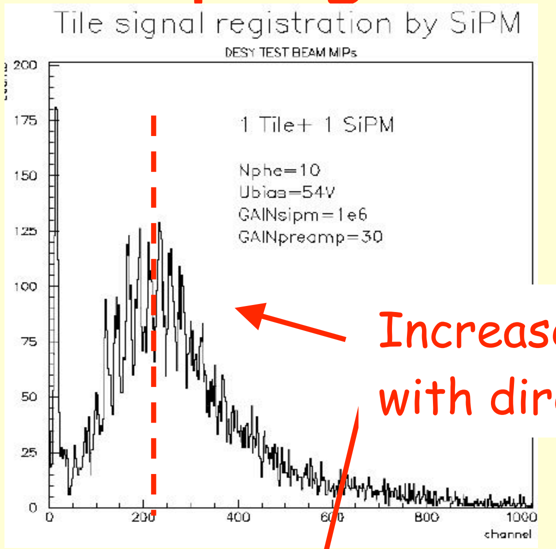
higher light yield

Fiber Coupling

Compare fiber readout:

SiPM 576 px
+60 cm WSL
fiber couple

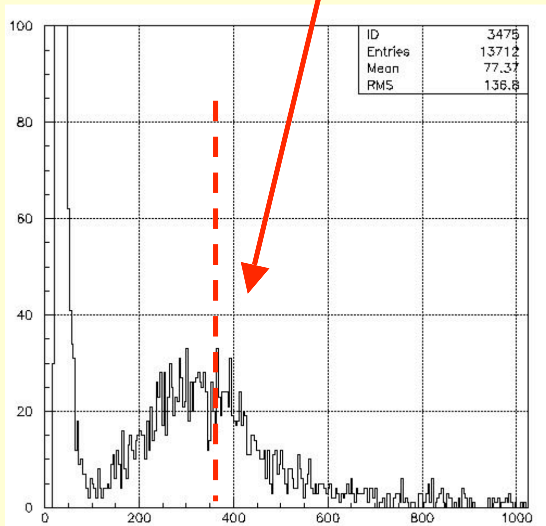
➔ 10 pixels



Increase light yield
with direct coupling

SiPM 1000 px
Directly couple
on tile

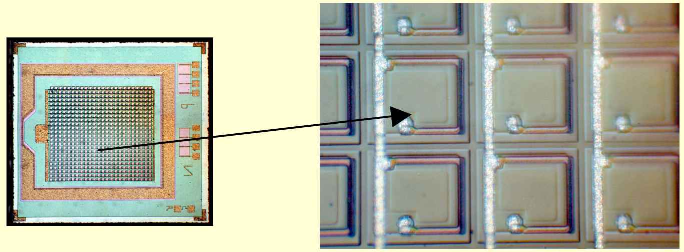
➔15-25 pixels



From Elena Podova, MEFhI

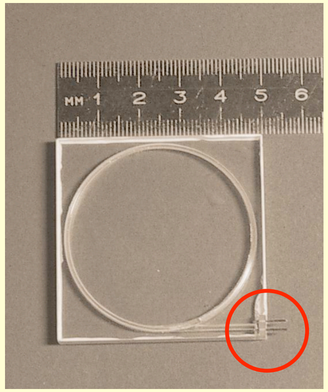
Photo Detectors

Silicon PhotoMultiplier (SiPM)
MEPhI&PULSAR



SiPM

Pixels of the SiPM



Silicon photo-multiplier (SiPM):

- new detector concept, first test with beam
- sizes: 1x1mm^2, 1024 pixels/mm^2
- gain ~ 2*10^6, quantum eff. ~ 15-20%
- single tile read out / mounted directly on tile

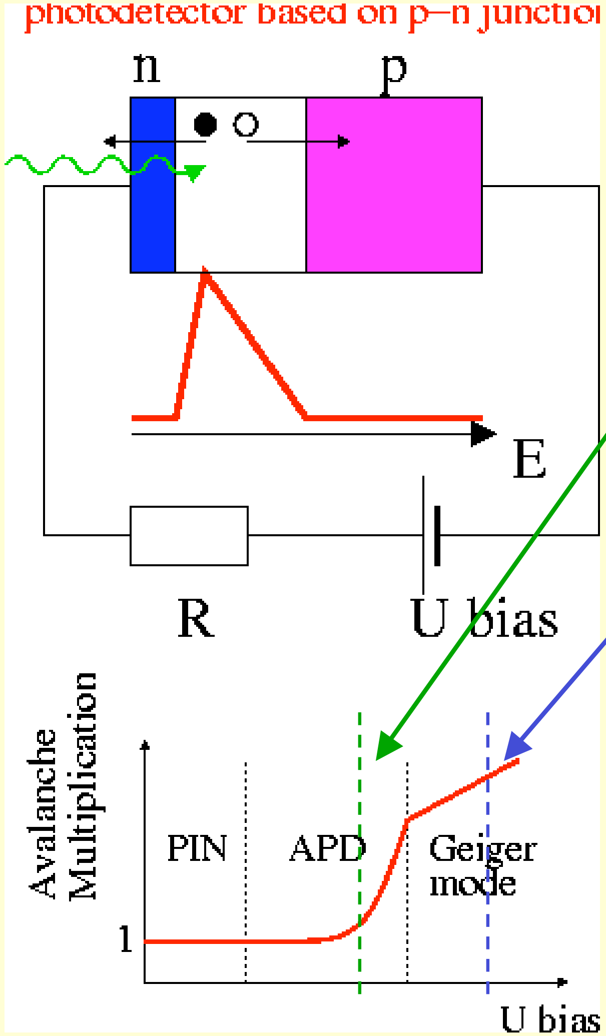
Avalanche photo-diode (APD):

- different from those used by CERN experiments
- 3x3mm^2 low capacity
- gain ~ 500, quantum eff. ~ 75%
- cell read out: 3 tiles

➔APDs are well known and studied at KEK !!!

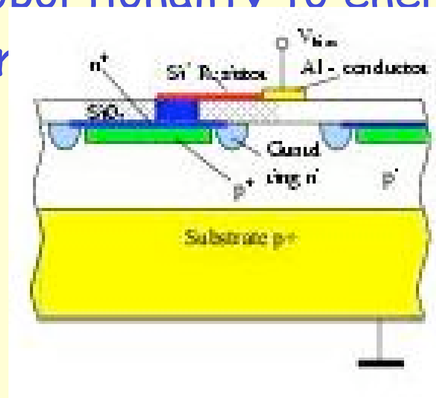
➔Focus on SiPM

Principle of operation

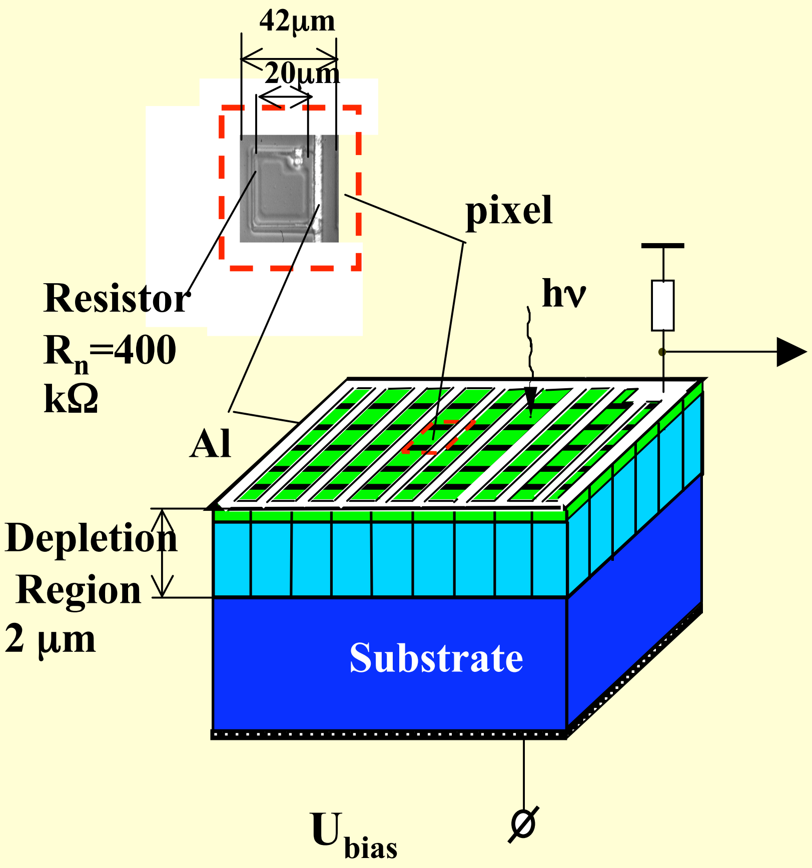


ADP operated with avalanche multiplication ~ 50-500
➔signal proportional to energy deposited

SiPM operated in Geiger mode avalanche multiplication ~$2*10^6$
- R = 400 kΩ prevents detector break down
➔Proportionality to energy is lost
➔Ser



SiPM main characteristics



➢Pixel size ~20-30μm ➔ important quantity:

Inter-pixel cross-talk

• electrical minimized by:

- decoupling quenching resistor for each pixel
- boundaries between pixels to decouple them electrically ➔ reduce sensitive area ➔ geometrical efficiency

• optical:

-due to photons created in Geiger discharge per one electron and collected on adjacent pixel

➢Working point: $V_{Bias} = V_{breakdown} + \Delta V \sim 50\text{-}60$ V

ΔV = 10-15% above breakdown voltage

Each pixel behaves as a Geiger counter with

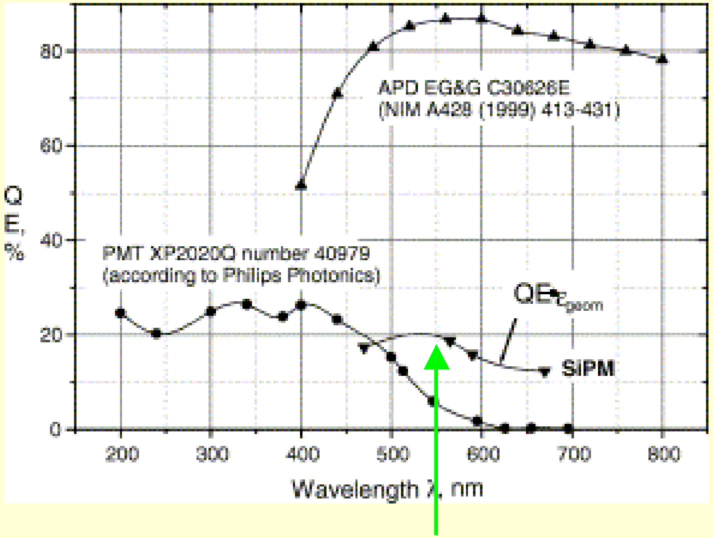
$Q_{pixel} = \Delta V\, C_{pixel}$

with C_{pixel}~50fmF ➔ Q_{pixel}~300fmC=2*10^6e

Dynamic range ~ number of pixels ➔ saturation

SiPM main characteristics (II)

Depletion region is very small ~ 2μm
➔strong electric field (2-3) 10^5 V/cm
➔carrier drift velocity ~ 10^7 cm/s
➔very short Geiger discharge development < 500 ps
➔pixel recovery time = (C_{pixel} R_{pixel}) ~ 30 ns



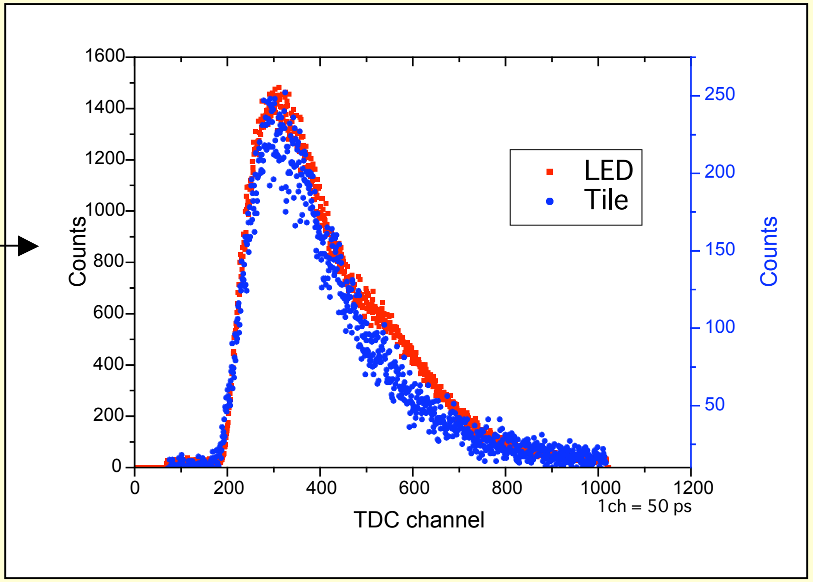
WLS fiber emission

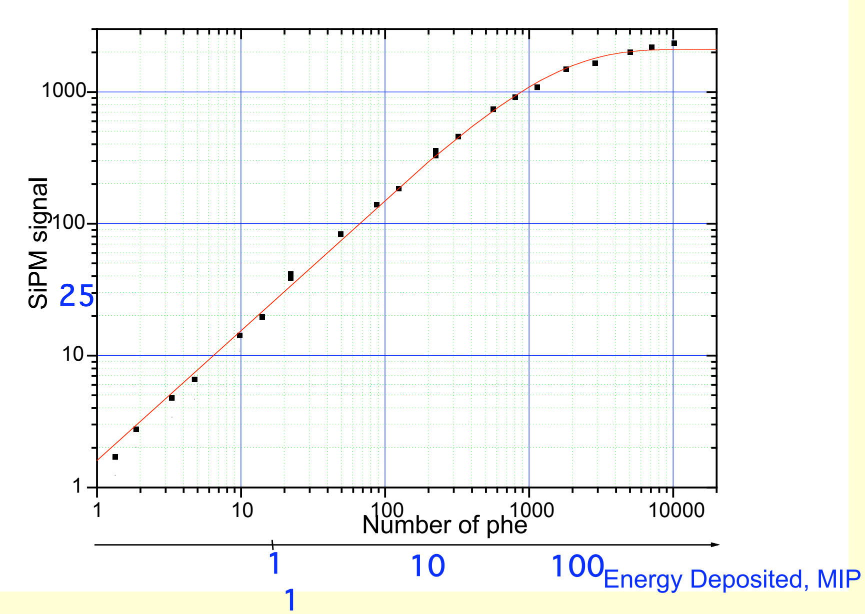
Photon detection efficiency (PDE):
- for SiPM the QE (~90%) is multiplied by Geiger efficiency (~60%) and by geometrical efficiency (sensitive/total area ~30%)
- highest efficiency for green/blue light
  ➔ important when using with WLS fibers

Temperature and voltage dependence:
-7 °C ➔ +3% Gain and PDE
+0.15 V ➔ +3% Gain and PDE

SiPM response function

Response curve measured with LED pulse shape similar to tile response to MIP (~ 15 ns FWHM)





➔1024 pixel SiPM saturates at ~ 2000 effective pixels:

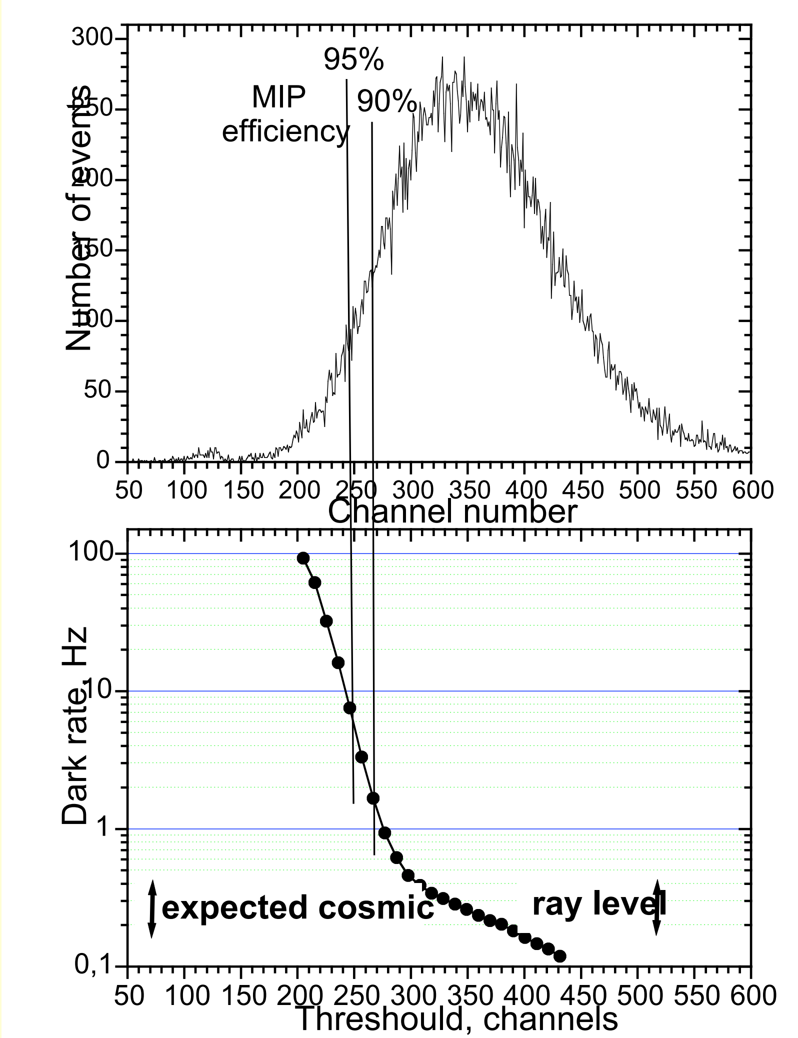
- very short recovery time ~ 10 ns
- each pixel is fired in average twice during the duration of the tile+WLS fiber signal

SiPM dark rate

Spectrum of β-electrons from Sr^{90} source on tile-fiber system with SiPM readout

efficiency ~ 90%
➔ dark rate ~ 2 Hz
Determined by optical crosstalk between adjacent pixels

➔Ongoing studies at MEPHI/PULSAR
to reduce dark rate

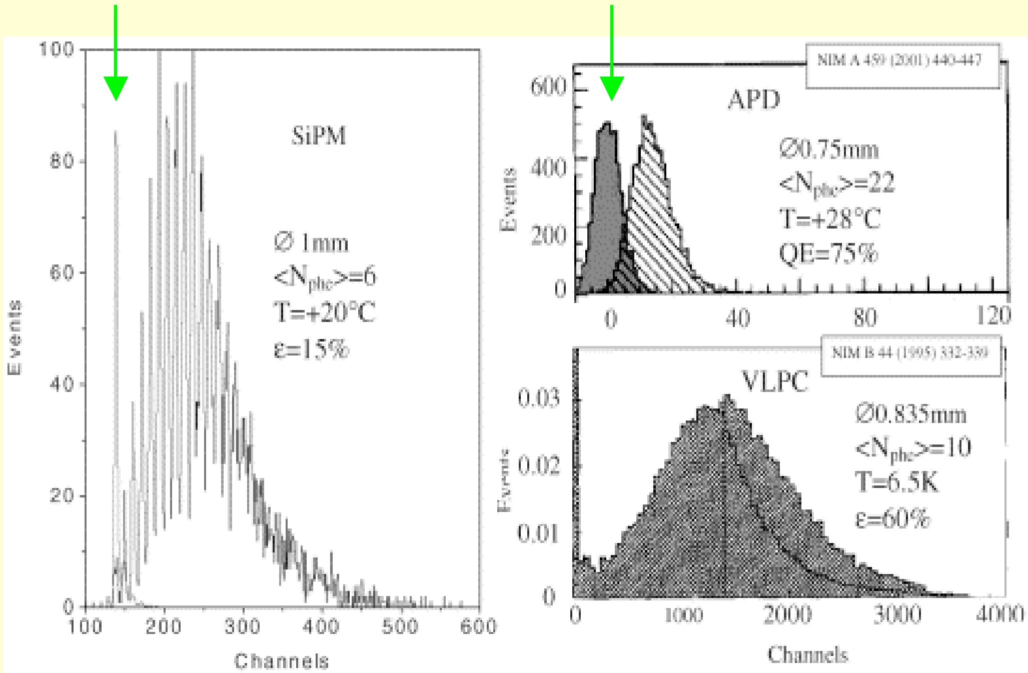


Signal to Noise ratio

Signal to noise ratio of SiPM at room temperature compared to APDs and Visible Light Photo Detectors

➔Improvement w.r.t. APD due to absence of electronics noise (no preamplifier needed for SiPM) and low Excess Noise Factor (ENF) connected with Geiger discharge development (<1.05 for SiPM, 2-3 for APD)

Pedestal



Detector characterization

SiPM Z200

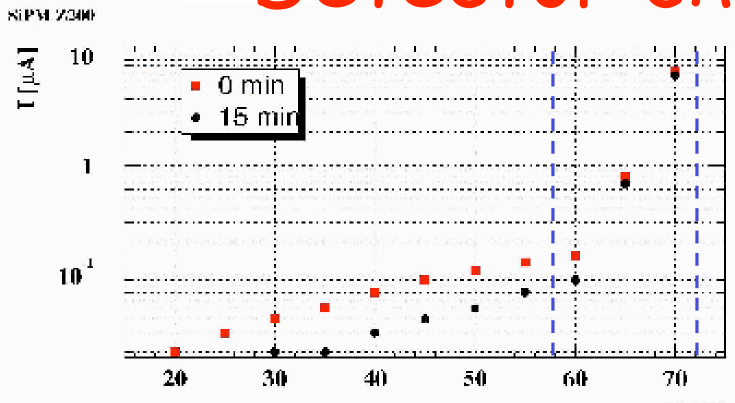


Fig 1: Current measurement for different voltages (notice log-scale)
- high systematic uncertainty due to electronical noise
- difference in measurements due to relaxation

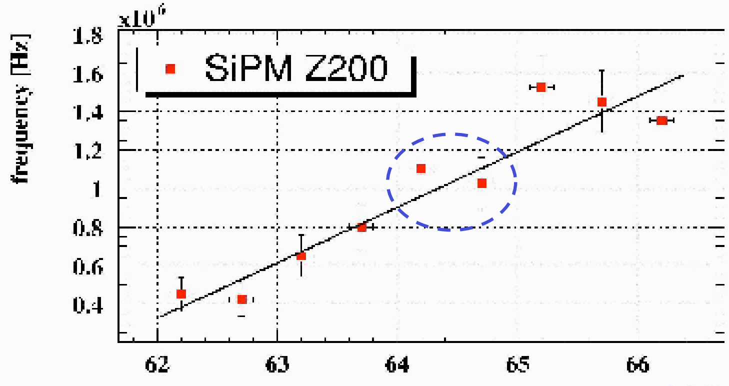


Fig 2: Noise measurement for different voltages
- low statistic

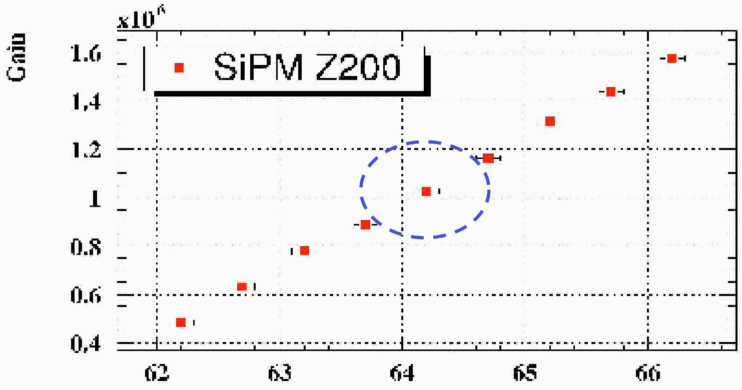


Fig 3: Gain measurement for different voltages

- find working point:

~10-15% above breakdown voltage

- optimize working point for:

Noise frequency ~ 1MHz

Gain ~ 10^6 e

The MiniCal Prototype

First working prototype of Analogue HCAL:

Study of energy resolution and shower shape
Control calibration and monitoring

Compare with MC prediction ➔ tune MC
Study various photo-detectors against tuned MC

Saturation effects in the range 1 – 7 GeV
➔ dynamic range
➔ linearity

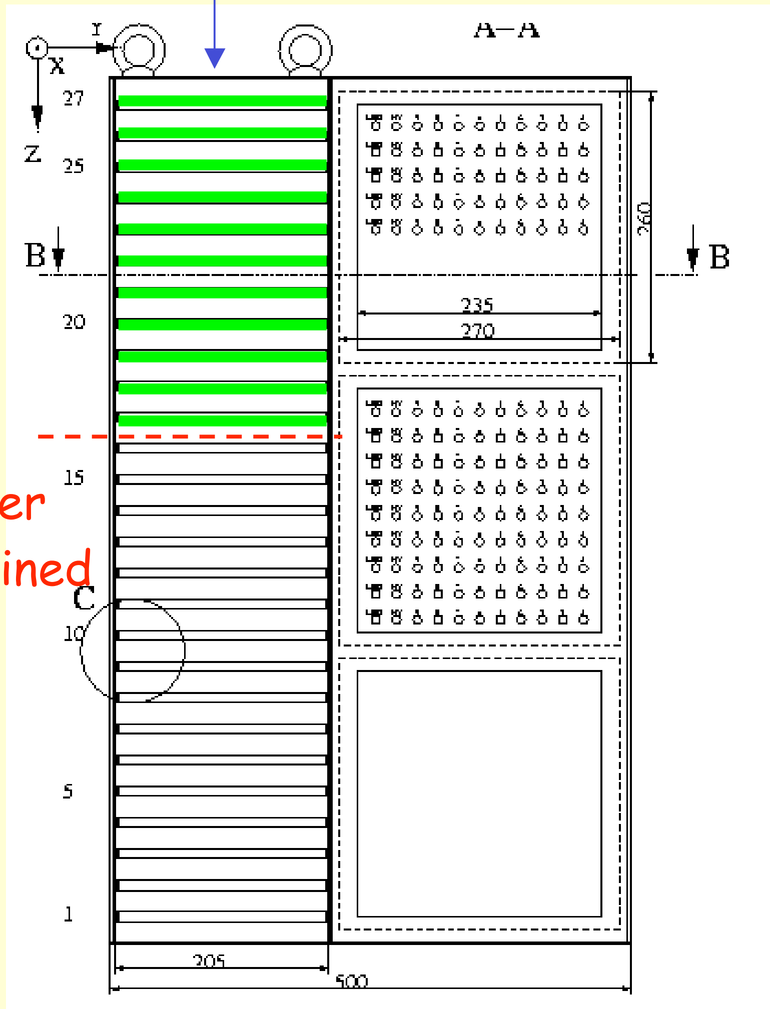
get detector hardware under control !!!

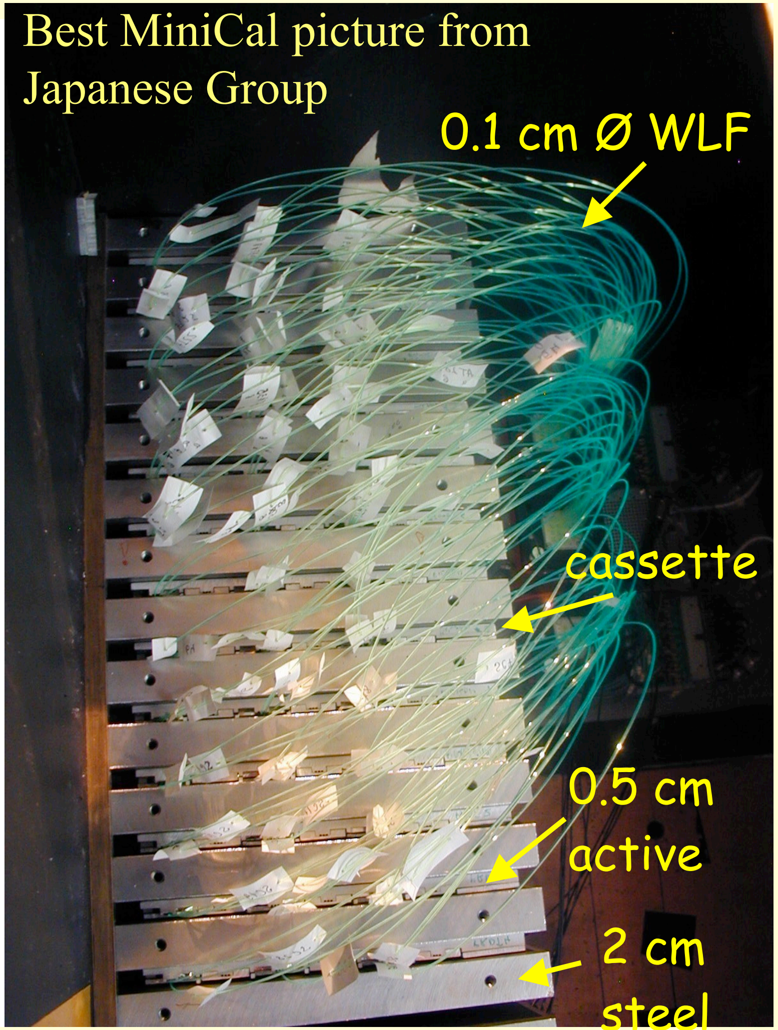
Get ready for studies on Physics Prototype …

The MiniCal Prototype

e^+ 1-6 GeV

97% Shower contained





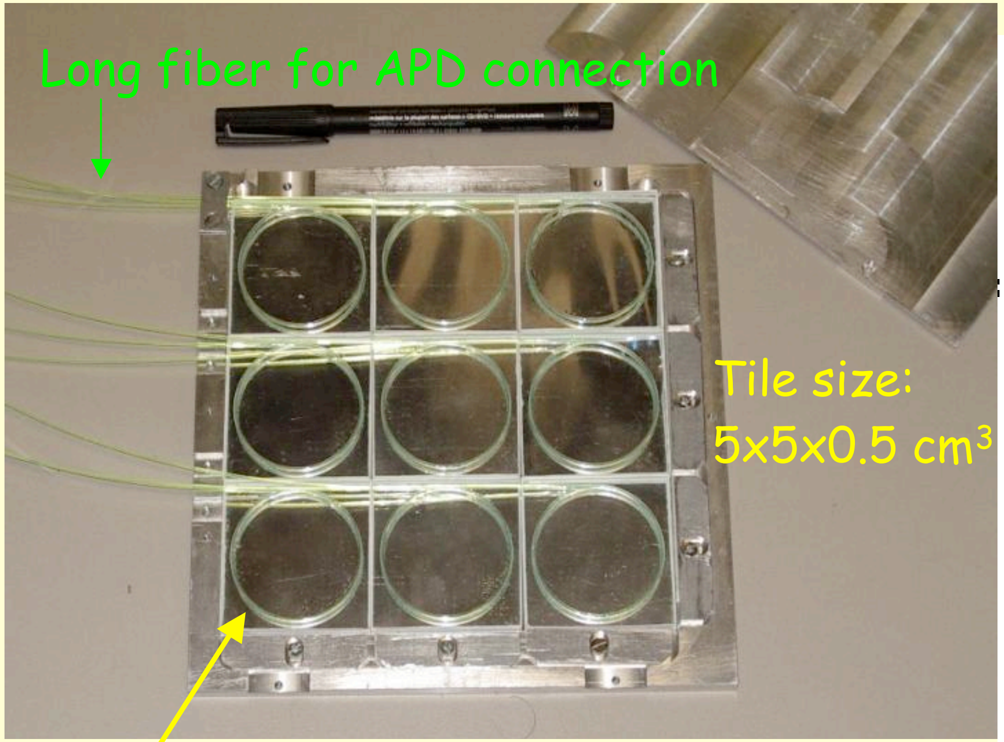
0.1 cm Ø WLF

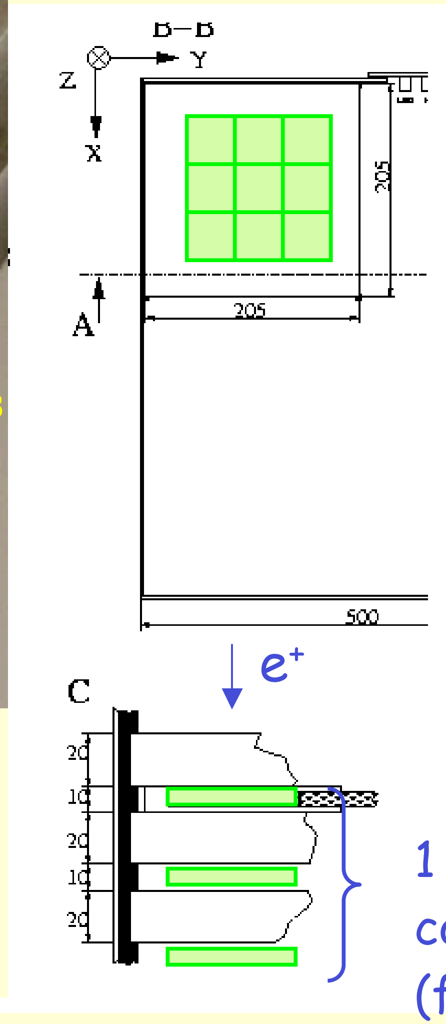
cassette

0.5 cm active

2 cm steel

The Cassette structure





3x3 tiles / layer

1-loop fiber placed in groove (not glued)
Single tiles covered by 3M reflector

1 cell = 3 tiles combined in depth (for PM/APD)

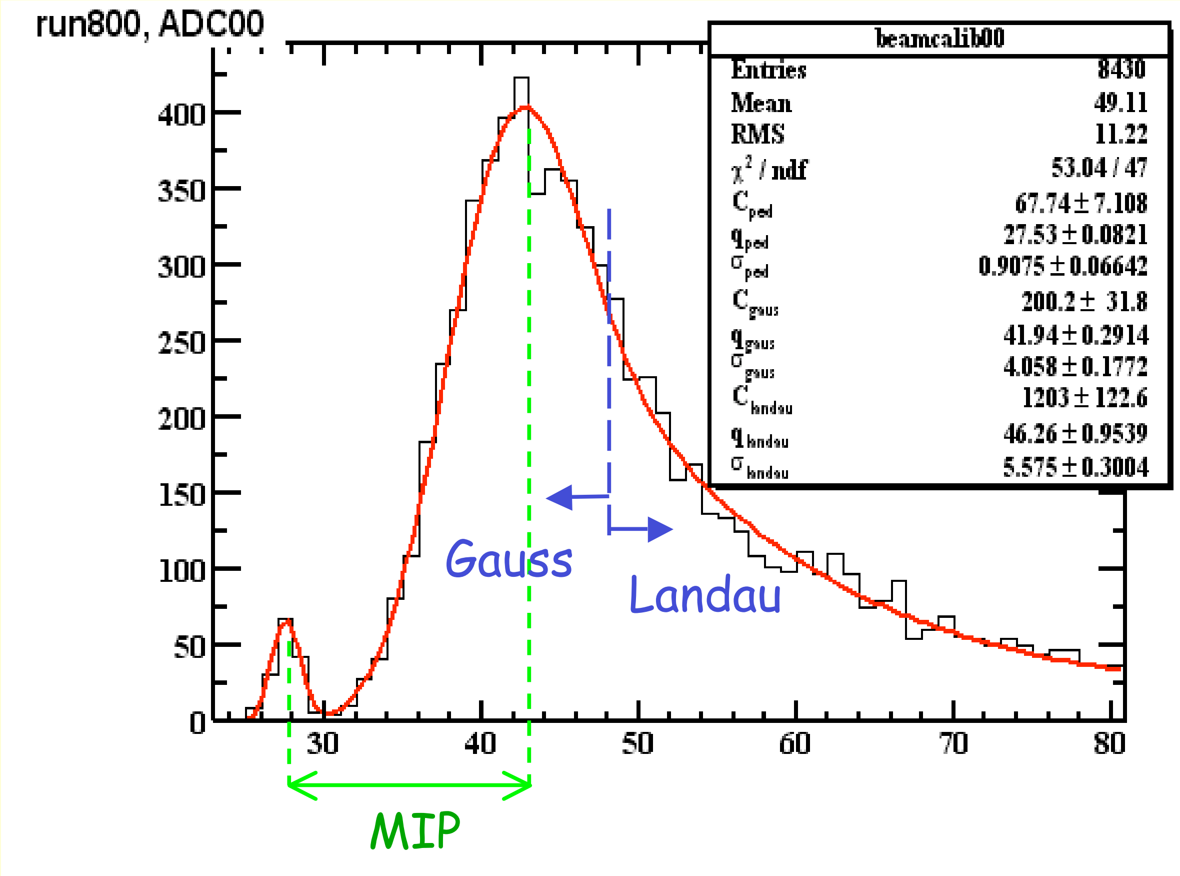
MIP Calibration for PM

➔ Obtained using 3 GeV electron beam on single tile, w/o absorber in front

MIP = MPV – pedestal

• Gauss for peak position
+ Landau for tail

• Pedestal determination:
1 ADC channel shift = 1% uncertainty in σ/E

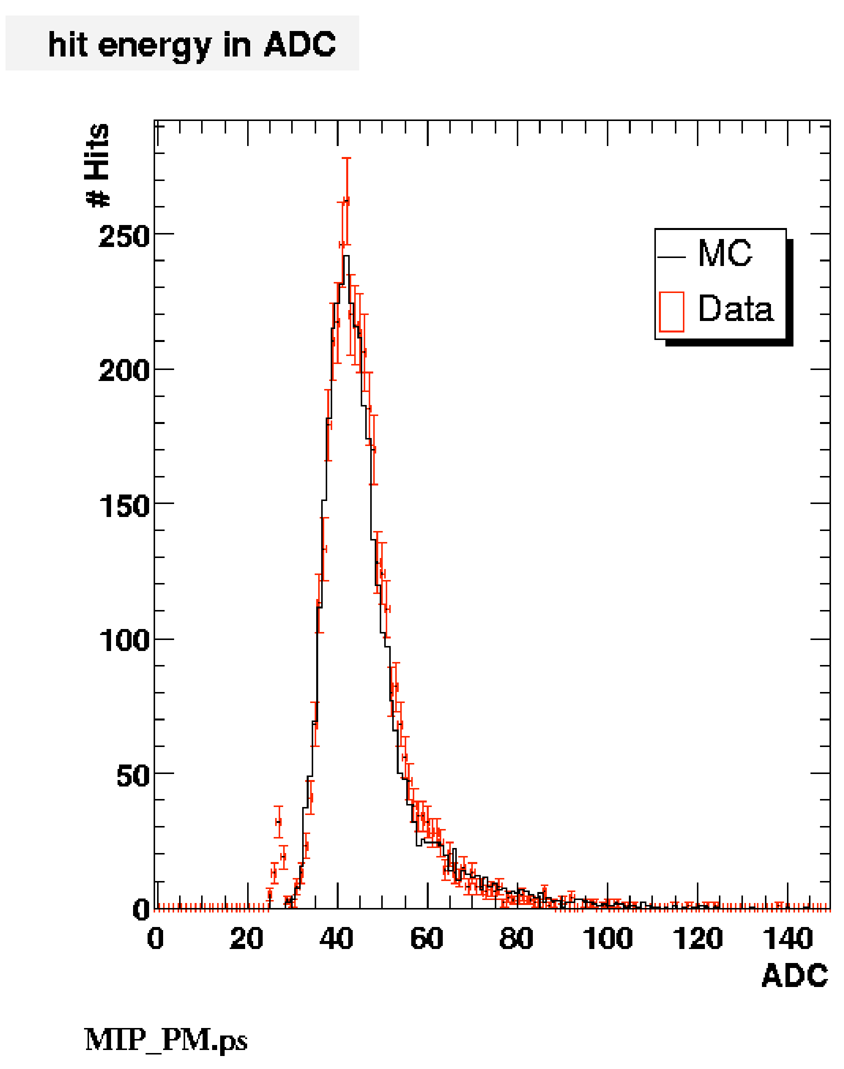


MC simulation of MIP

- detector description implemented in GEANT4
- MC has to be smeared according to detector properties

- single tile MC calibration needed:
  - # photo electrons /MIP
  - width of 1st photo electron

- good description of MIP shape after MC calibration

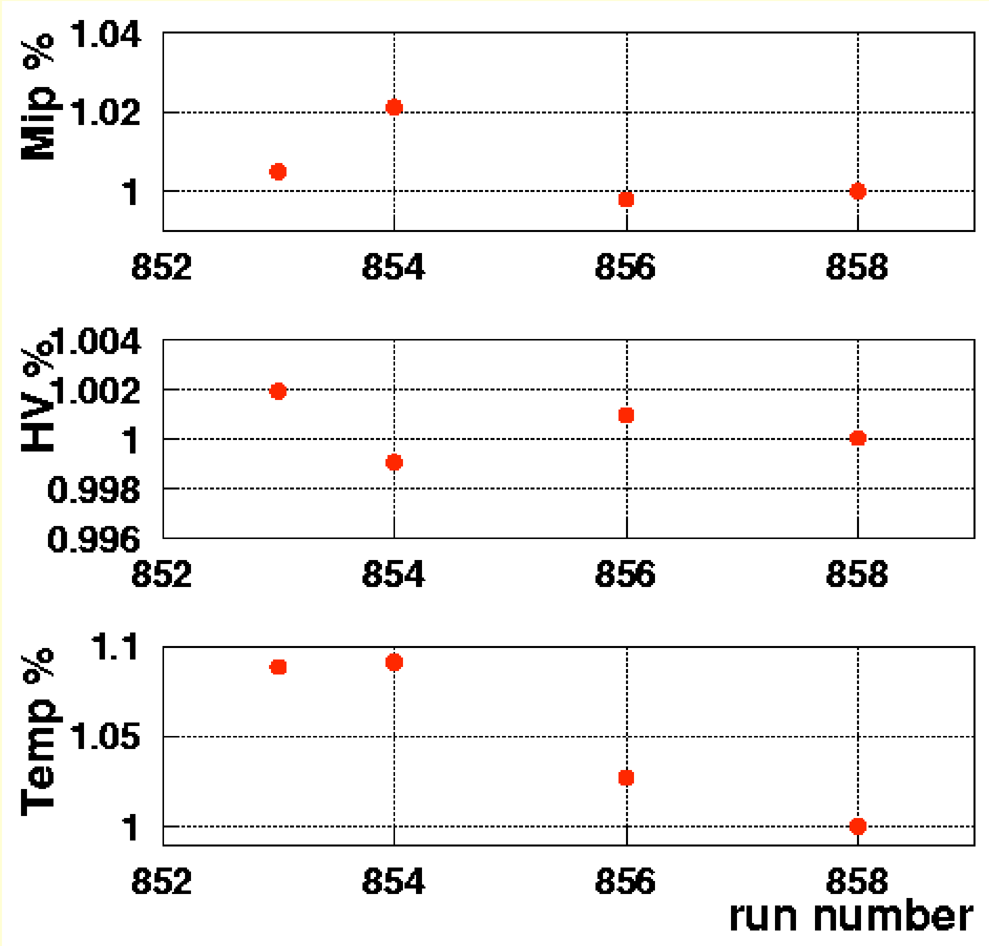


Slow Control Monitor

Daily monitor of MIP calibration versus:
- temperature fluctuations
- High Voltage stability

(example for PM monitoring)

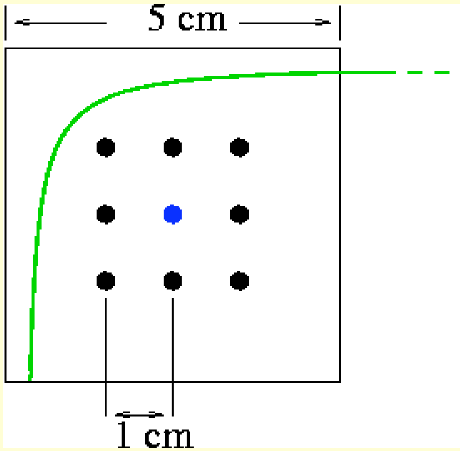
➔ 2% calibration reproducibility

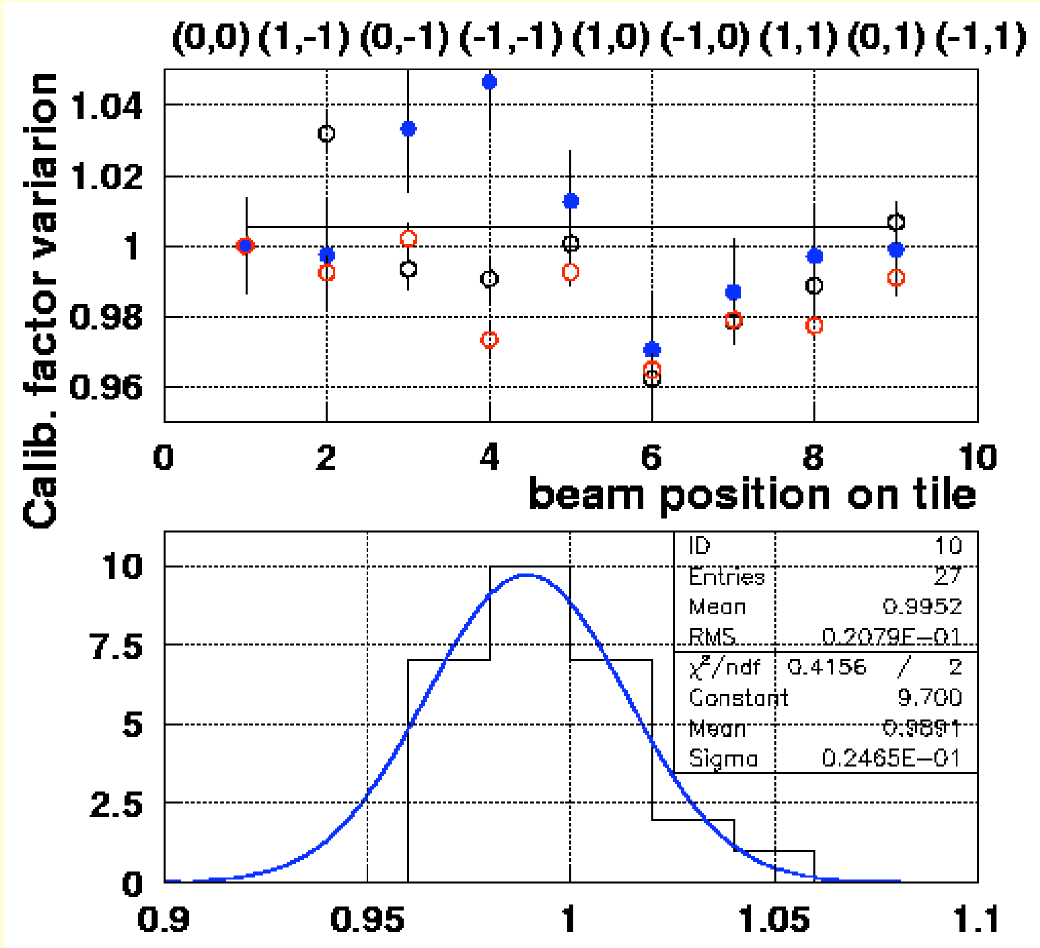


➔ related to temperature variation

Tile Calibration Scan

9 point scan of the tile centre according to:

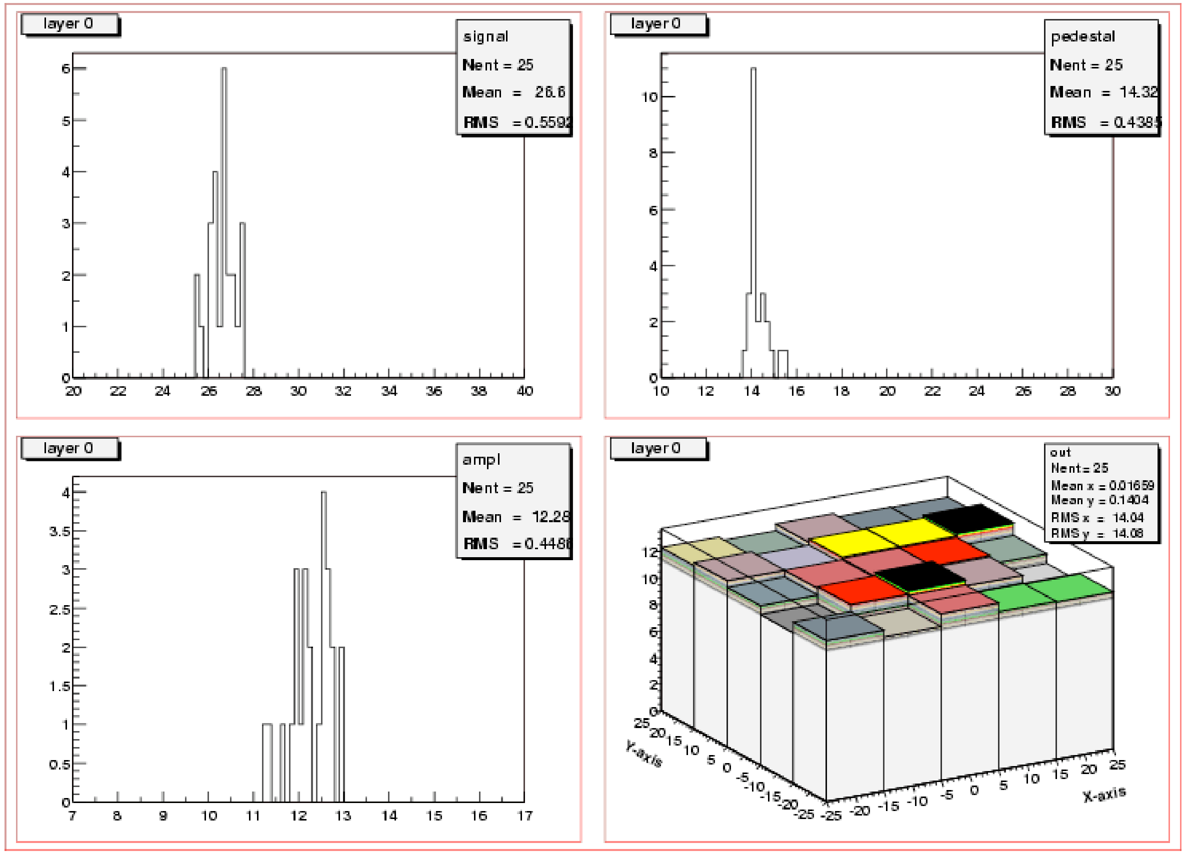




➔2% possible calibration uncertainty due to tile inhomogeneity

Tile homogeneity

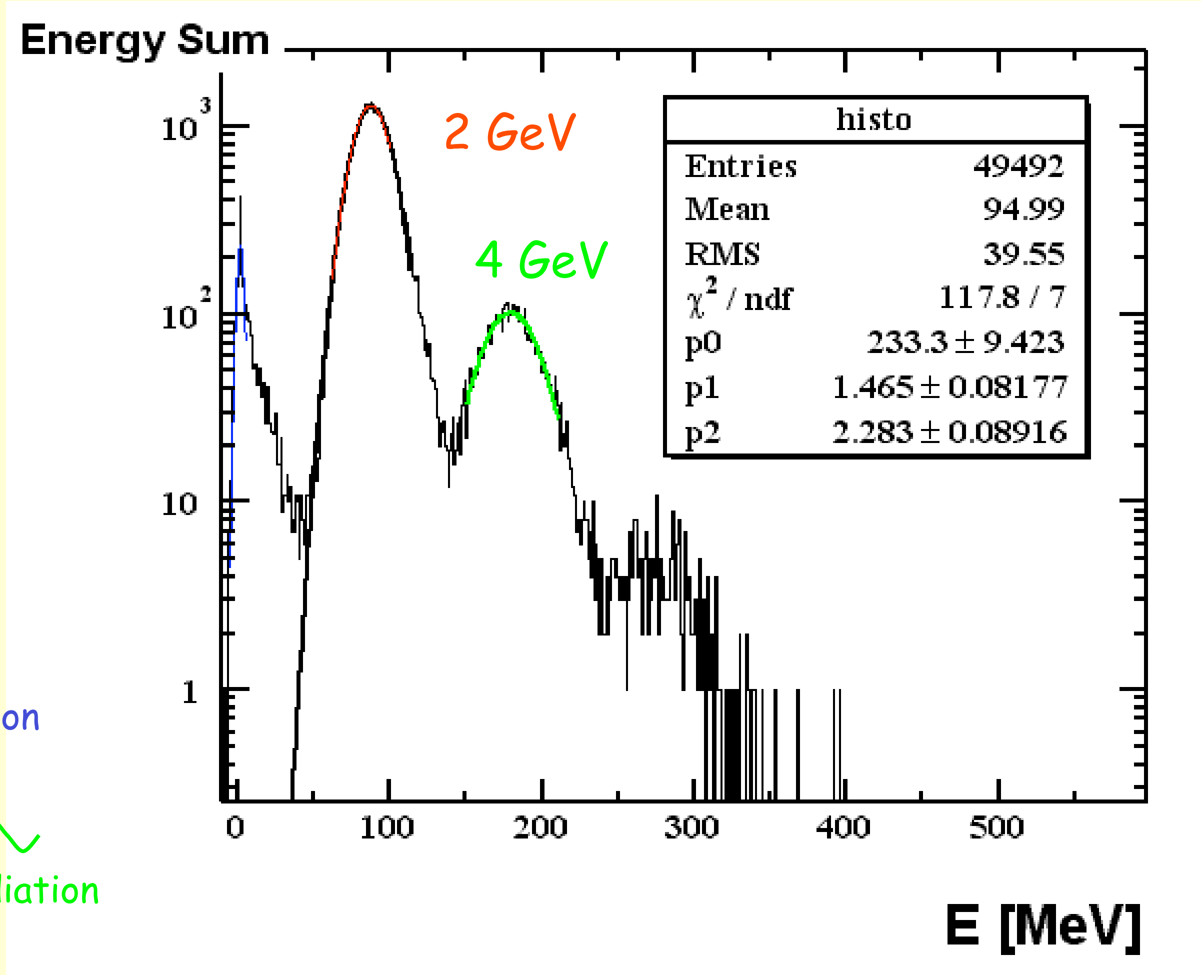
25 points scan over tile ➔ homogeneity better than 4%



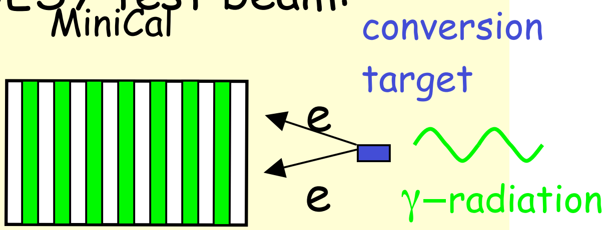
Two Particle Events

~8% of events have
2 particles hitting the
MiniCal

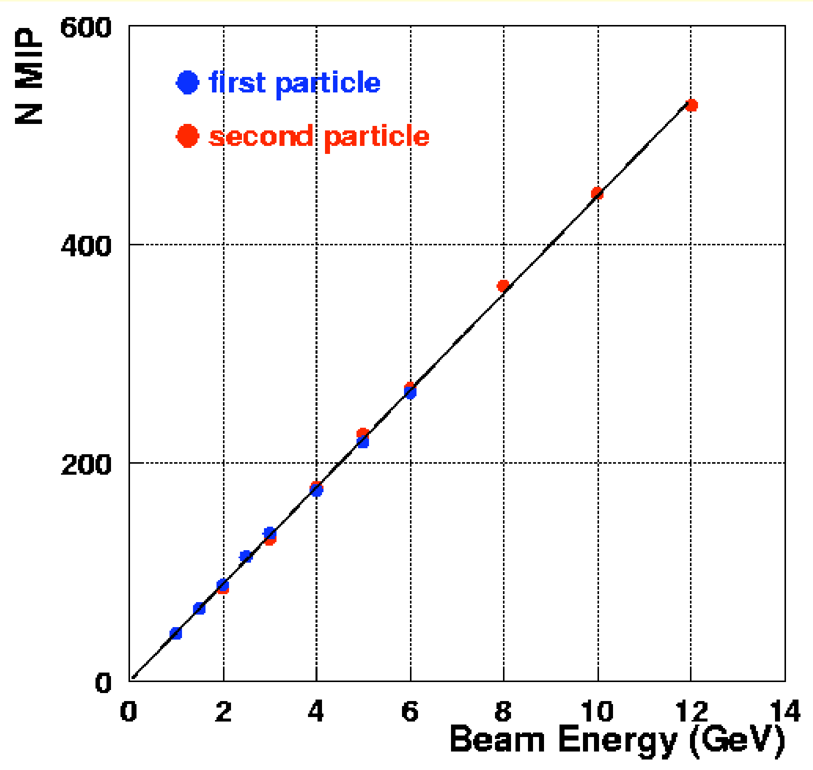
2 particles from
2 GeV beam give the
second peak @ 4 GeV
➔Max energy = 12GeV

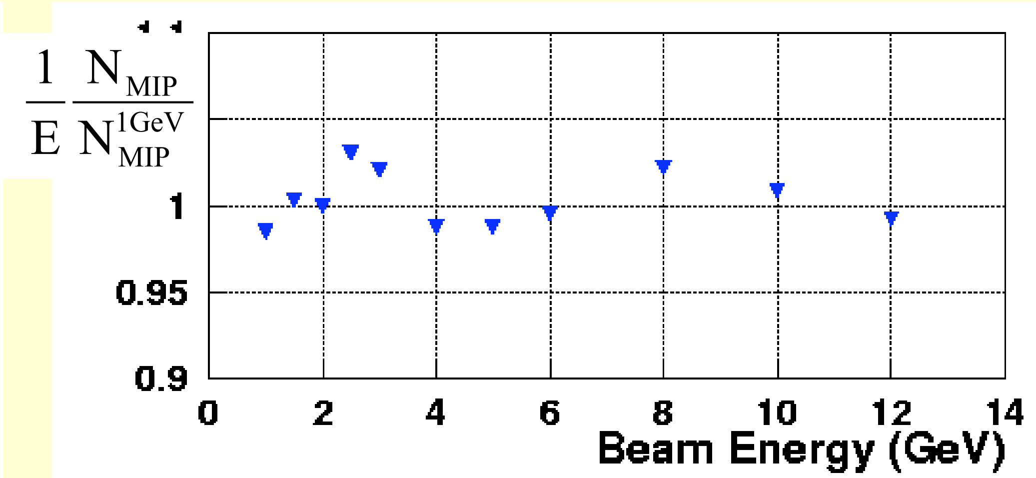


DESY test beam:



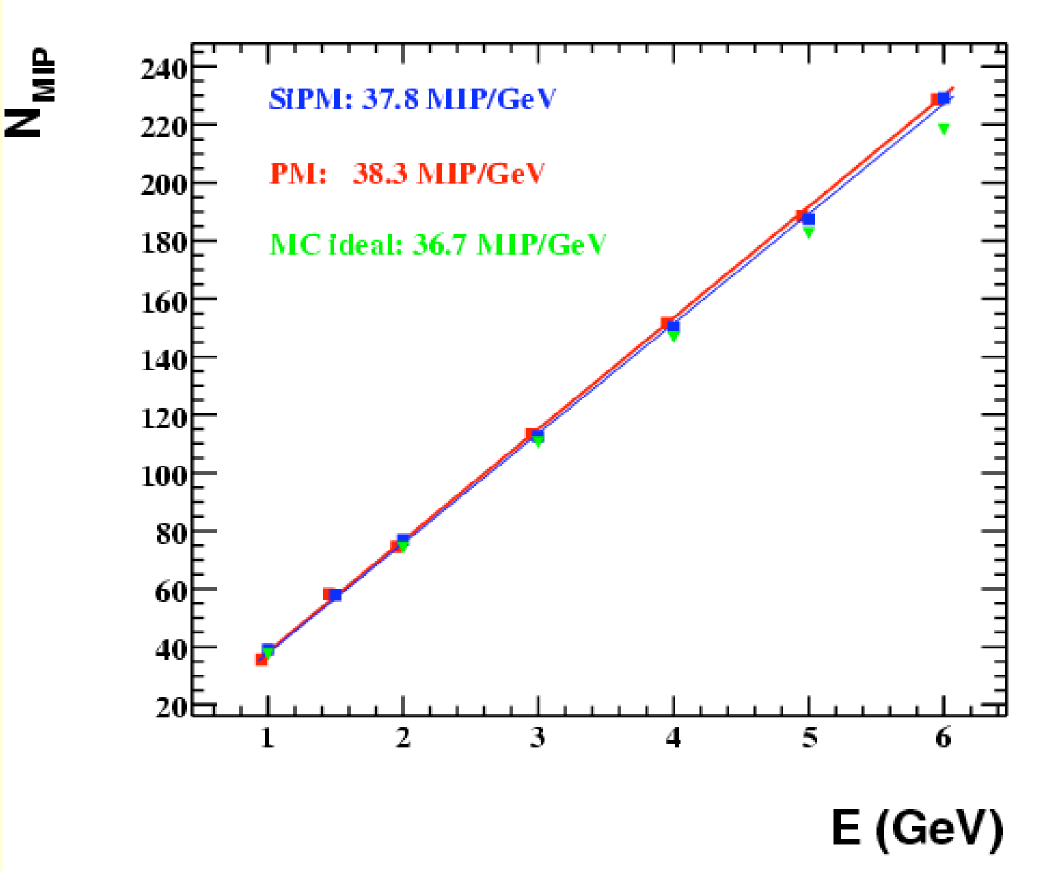
Linearity of PM Response





➔3% PM non-linearity
up to 12 GeV

Results comparison: N MIP

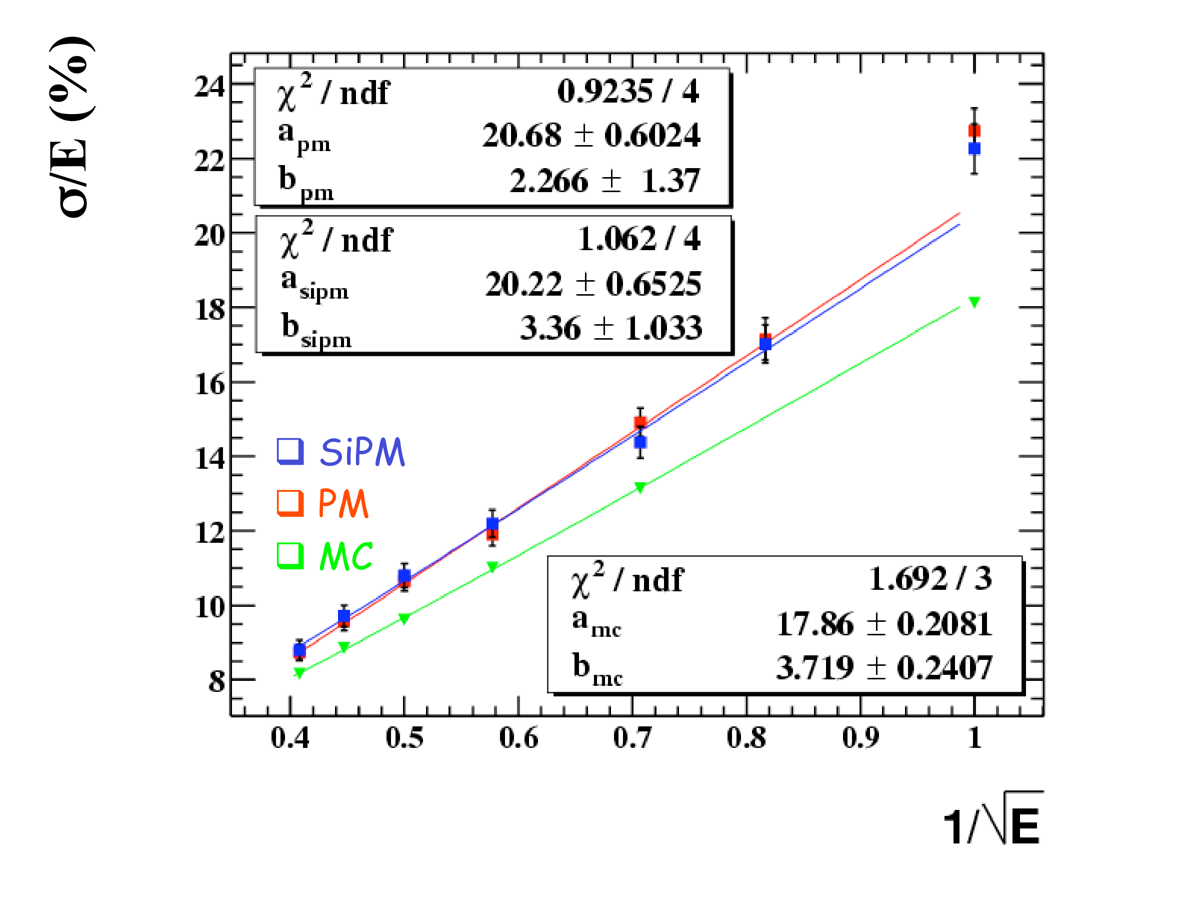


Sum of total energy deposited in calorimeter calibrated in number of MIPs

➔Very good agreement between SiPM and PM

➔Ideal MC does not include detector properties, just MiniCal geometry

Energy Resolution

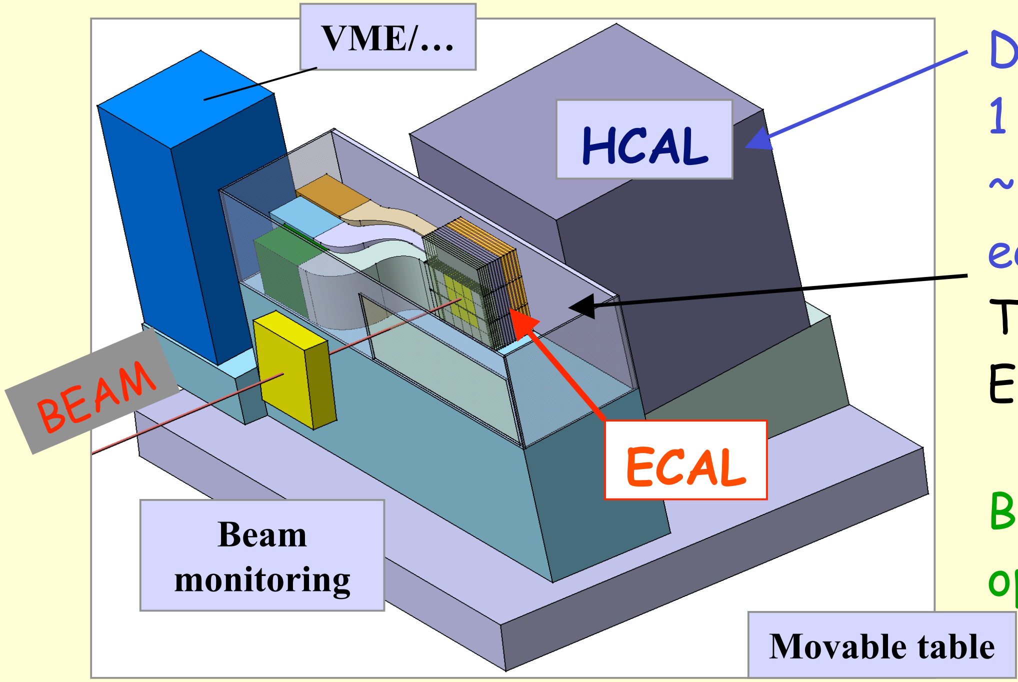


➔Problems with 1 GeV beam probably related to magnet hysteresis

➔Very good agreement between PM and SiPM

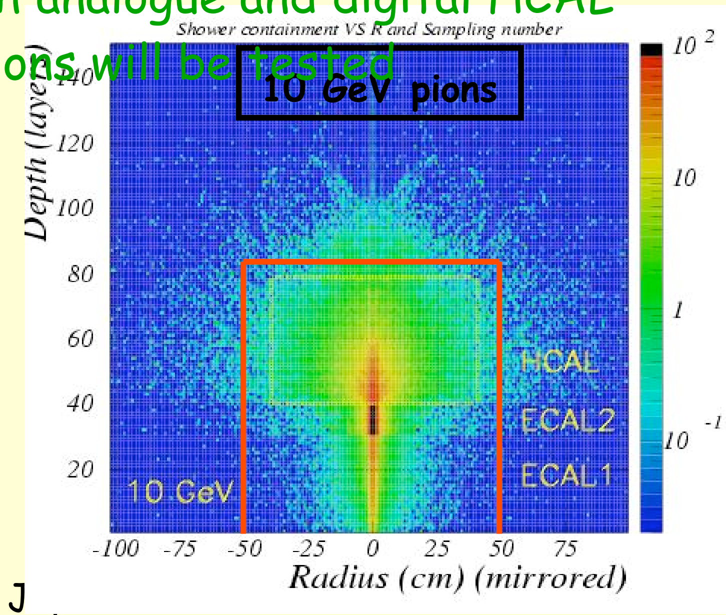
➔Ideal MC does not include detector properties, just MiniCal geometry

Future: the physics prototype



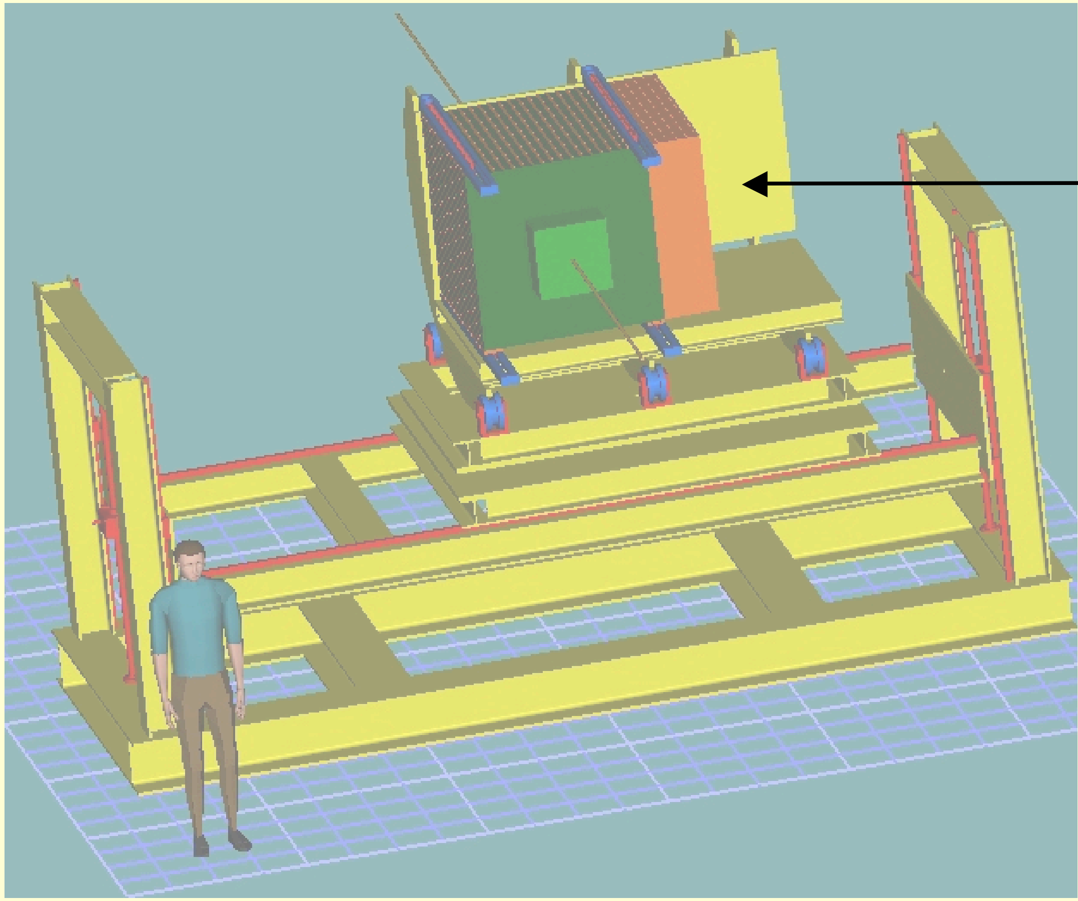
DESY project:
1 m³ Tile HCAL prototype
~ 8000 calorimeter tiles
equipped with SiPM
To be tested together with the ECAL prototype

Both analogue and digital HCAL options will be tested



➔ Tail catcher needed for full shower containment

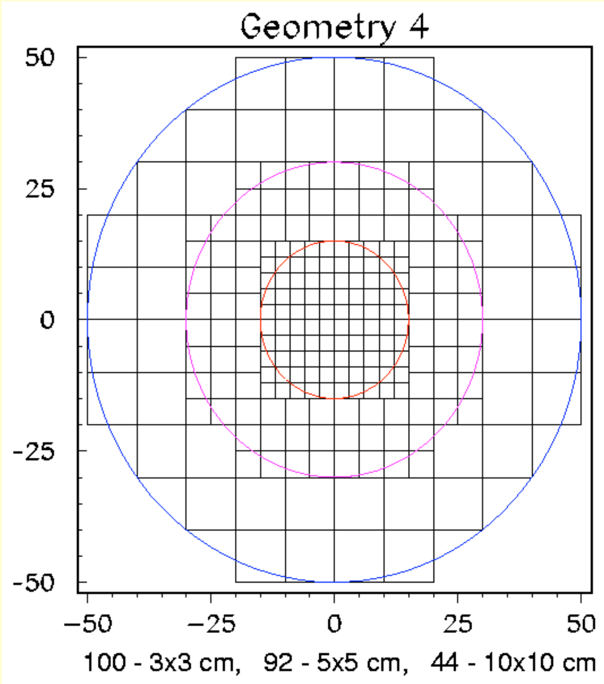
Mechanical structure

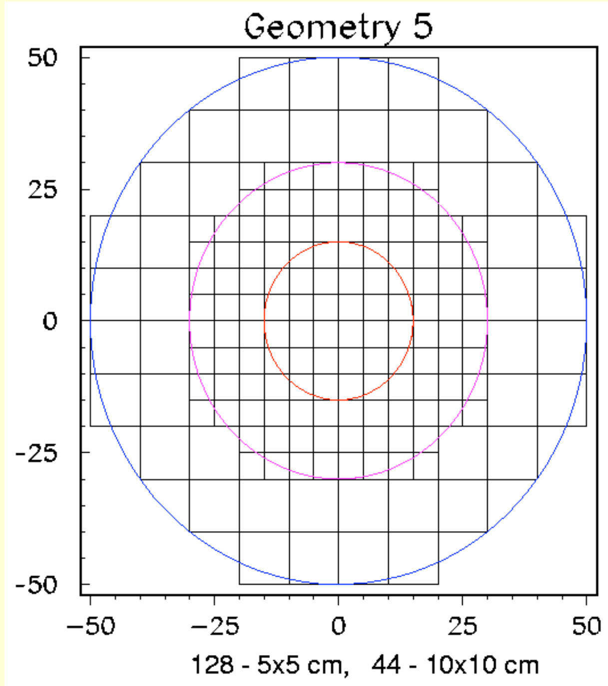


- Cassette insertion from the side
- VFE electronic
- VME-DAQ on platform

Beam height 2,30 m, platform: weight ~ 10 t, width ~ 5 m, depth ~ 2 m

Tile geometry for Physics Prototype





Total number of layers: 39

Tile sizes: 3x3 cm^2, 6x6 cm^2, 12x12 cm^2

Geometry optimization

- Define physical observable for optimization:

➔ Shower reconstruction/separation

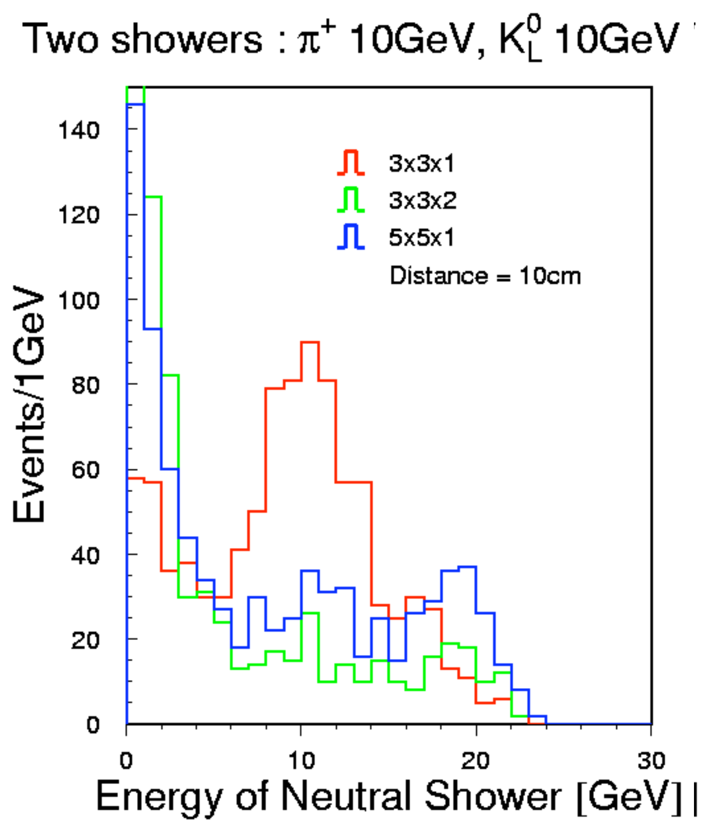
- Generate two 10 GeV showers initiated by $\pi+$ and K_0^L
- Use track information for $\pi+$
- Complete shower reconstruction algorithm used

(see papers from Vasilly Morgunov)

- Test three options of tile size and readout scheme:

  - 1 layer of 3x3 cm² tiles
  - 2 layers of 3x3 cm² tiles
  - 1 layer of 5x5 cm² tiles

- Compare to ideal particle flow algorithm

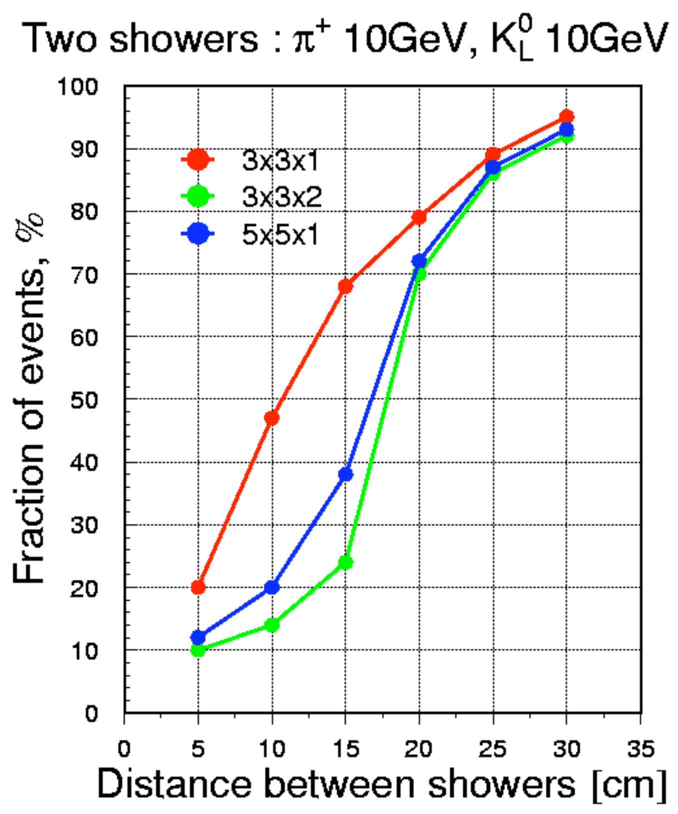


Geometry optimization

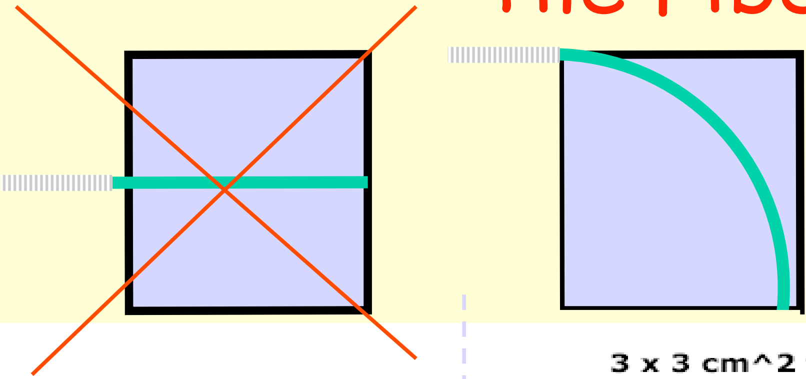
Shower separation quality is defined as the fraction of events in which the neutral shower is consistent with the energy in the case of ideal P-flow within 3σ.

Shower separation quality versus generated shower distance gives a good criterion for geometry comparison

➔ Final choice: 1 layer of 3x3 cm^2 tiles in the core



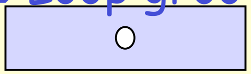
New studies for physics prototype: Tile Fiber System

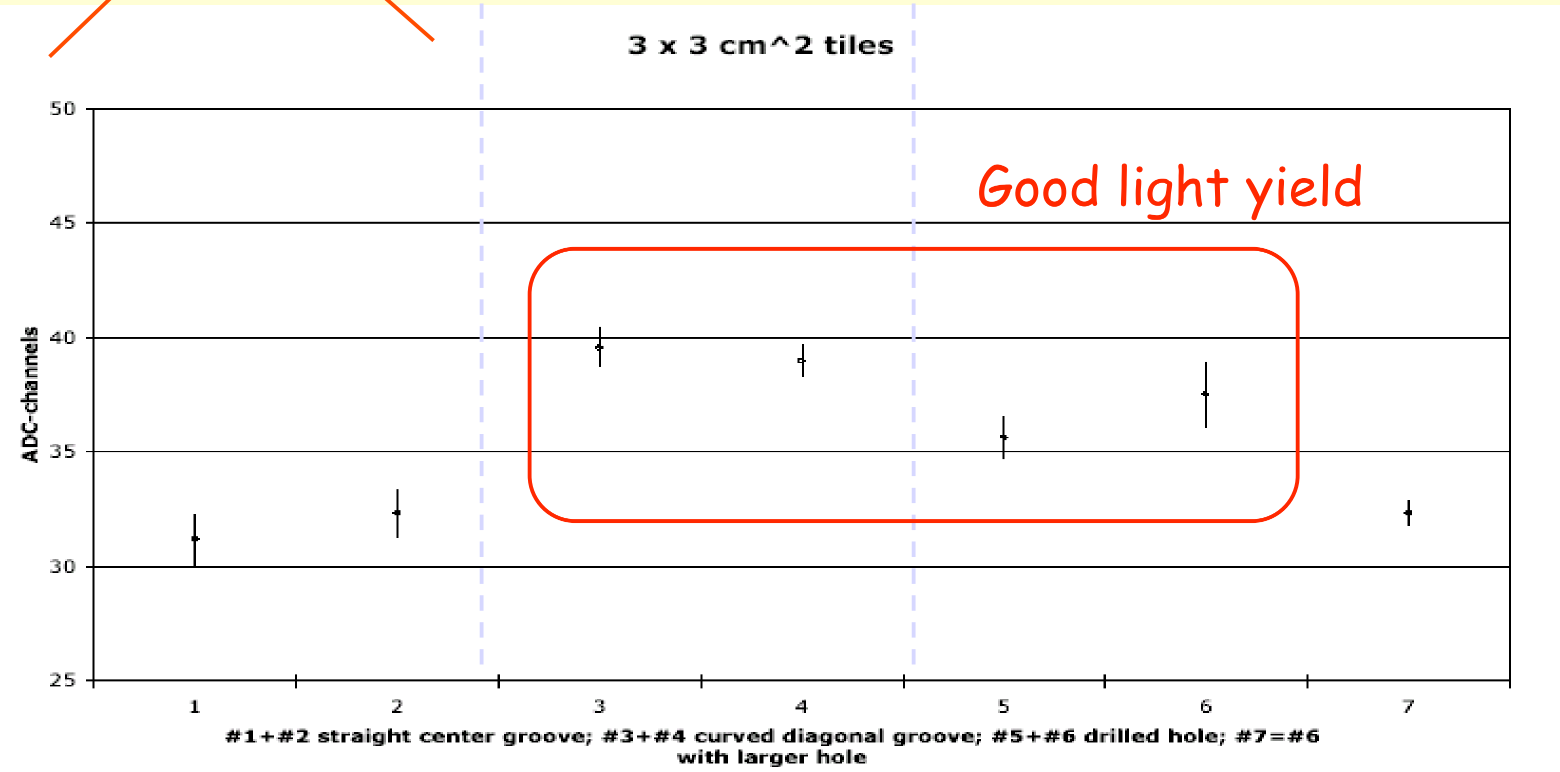


Reduced tile size to 3 x 3 cm^2:

➔Re-examine tile-fiber configuration

➔Loop groove not possible



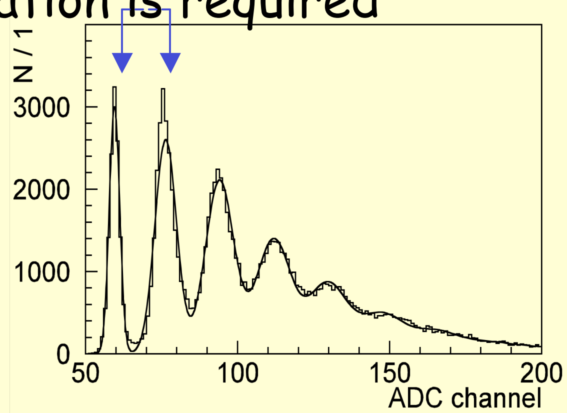


LED Monitoring

Next studies will focus on a reliable LED monitoring system for large number of tiles

Requirements:

- low light yield (~ 5-10 ph.e.) pre-amplification is required
  - ➔ to monitor SiPM gain ➔



- medium light yield (~ 25 ph.e ~ 1 MIP)
  - ➔ to monitor stability of MIP calibration
- high light yield (~ 200-500 ph.e.)
  - ➔ to monitor saturation behaviour

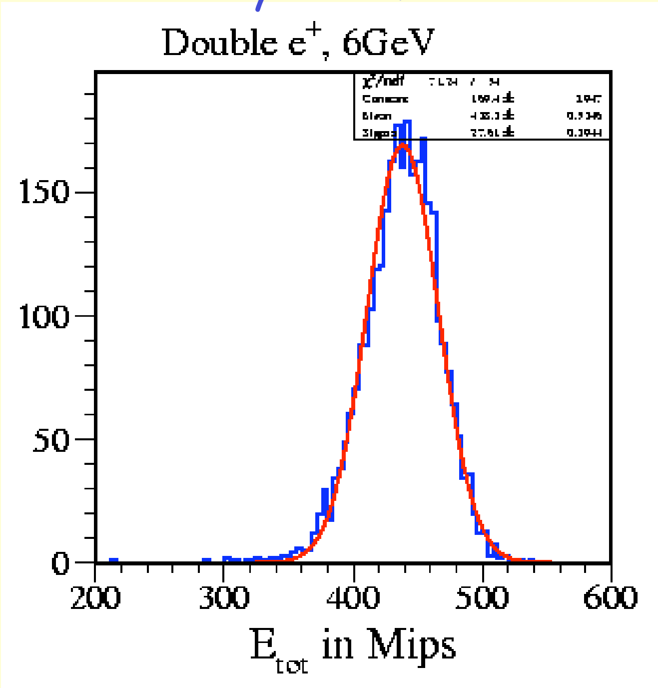
Outlook

- Successful test of MiniCal prototype with PM/SiPM readout
- Established SiPM technology for calorimeter readout
- ADP test still undergoing at DESY
  - ➔ exchange experience with KEK on APD and other photo-detectors

- Physics prototype under construction
- Geometry optimized for best shower separation
- First tests planed for beginning of 2005

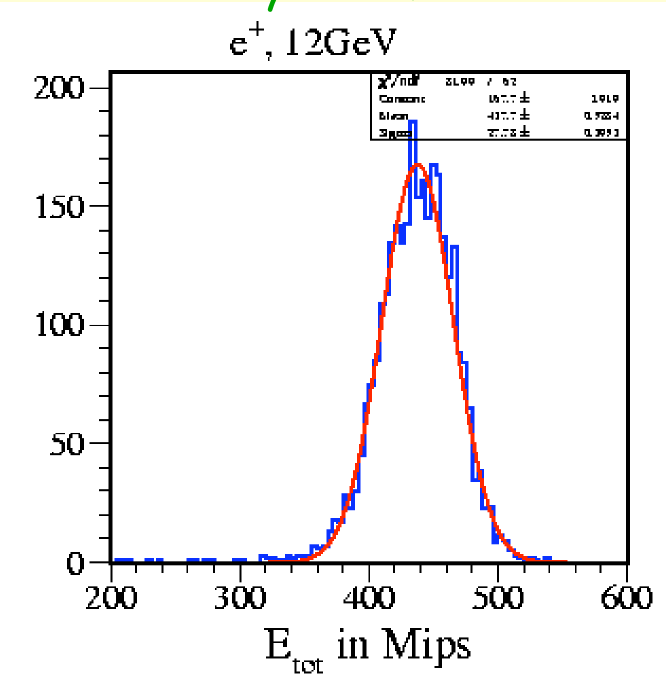
MC Simulation of Two-particle Events

13 layers MiniCal



Res. = 27.6/438.3 = 6.30%

26 layers MiniCal



Res. = 27.8/437.7 = 6.35%