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A scintillator tile hadron calorimeter prototype with a novel SiPM readout for ILC

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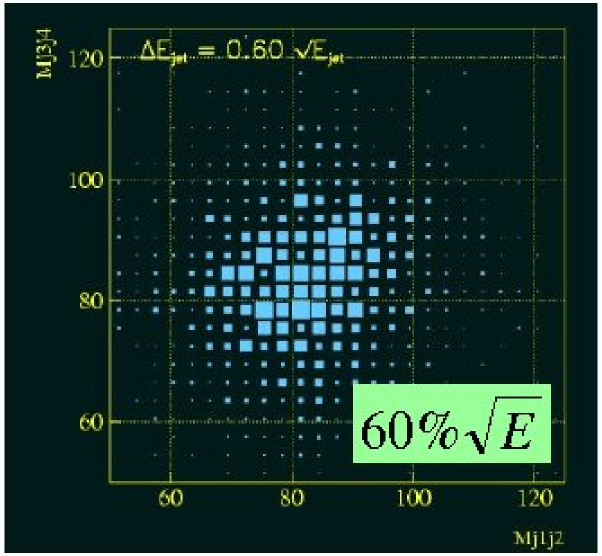
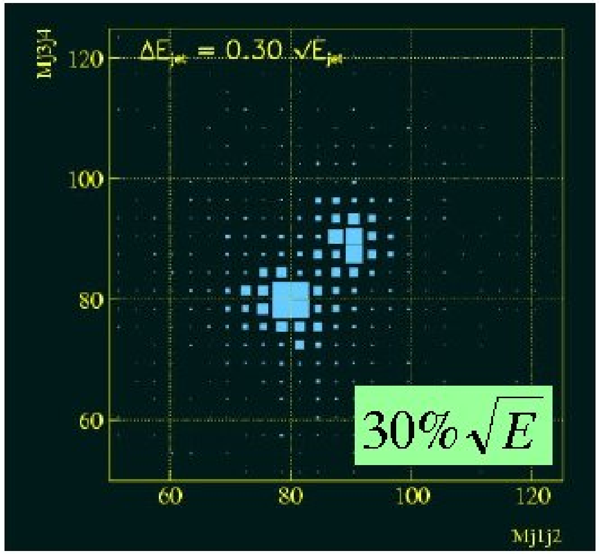
Representing the CALICE Collaboration

LC Physics goals require $\Delta E_J/\sqrt{E_J} \sim 30\%$





This can be achieved with Particle Flow Method (PFM):

⇨ **Use calorimeter only for measurement of K,n, and γ**

Substitute charged track showers with measurements in tracker

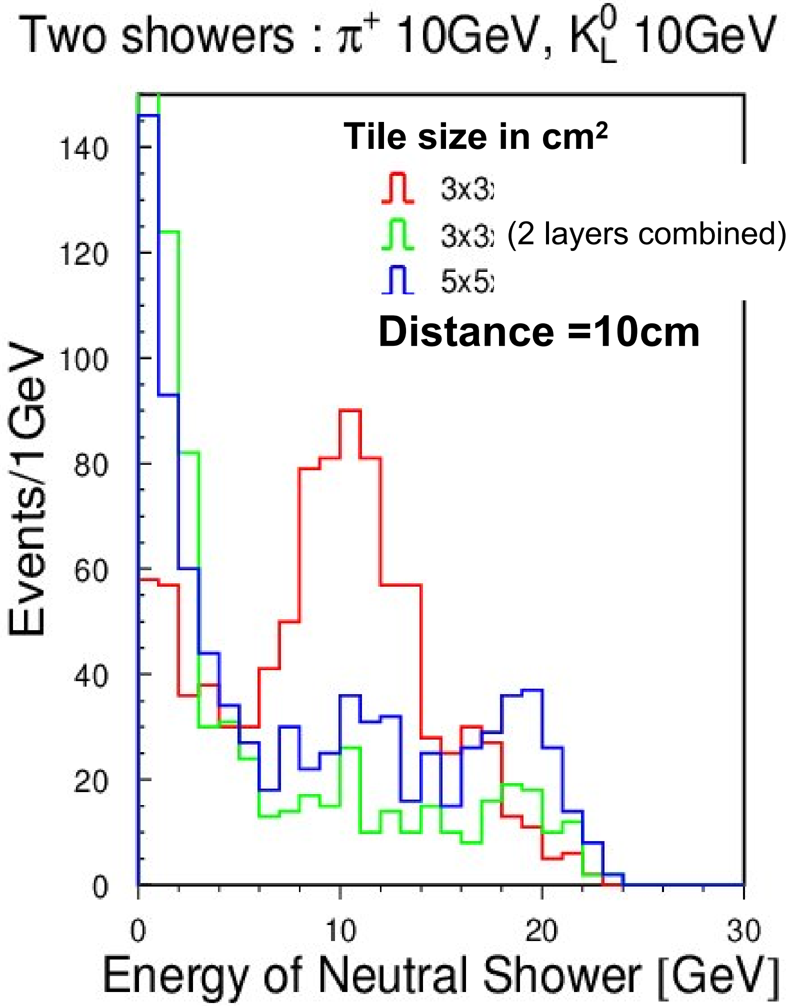
LC detector architecture is based on PFM, which is tested mainly with MC

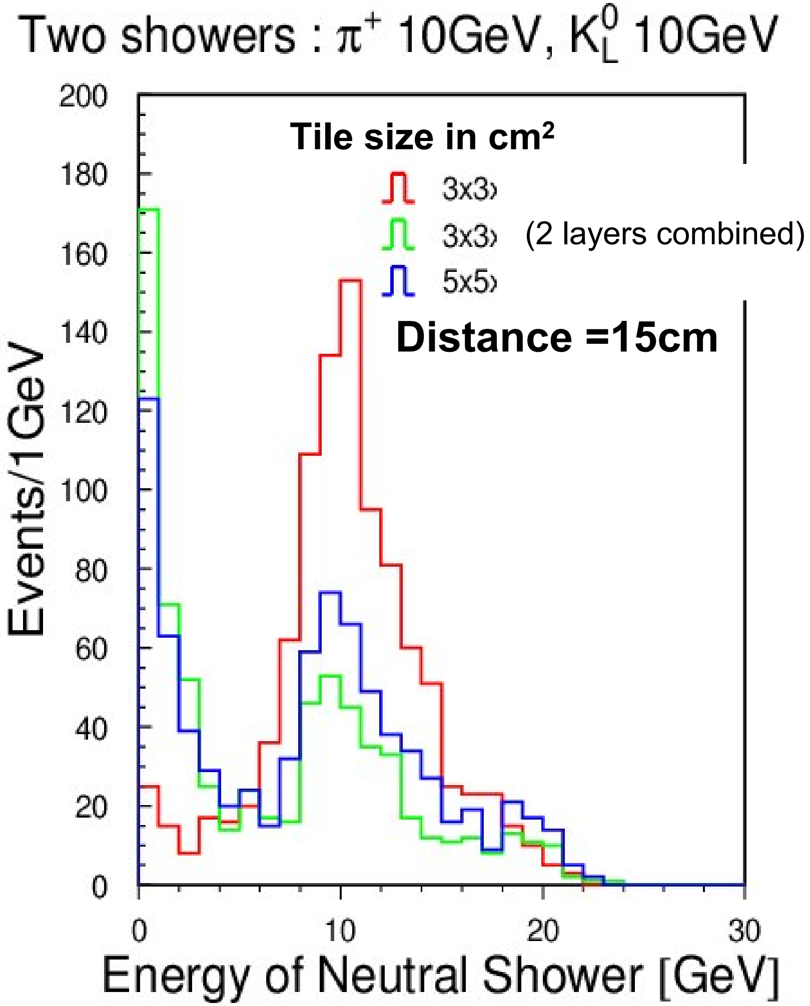
⇩

Experimental tests of PFM are extremely important

We are building now a prototype of scintillator tile calorimeter to test PFM

Shower Reconstruction/Separation

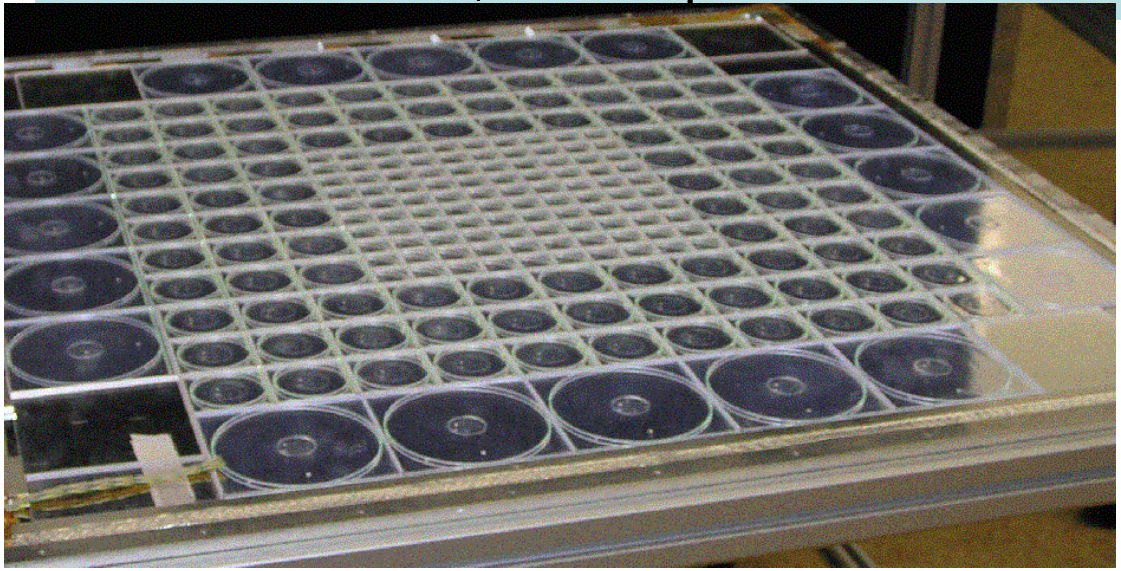


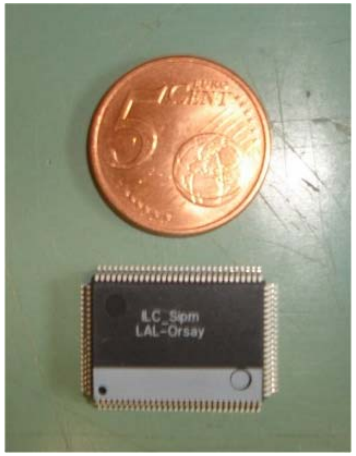


Very high granularity is required for Particle Flow Method

It can be achieved with novel photo-detectors - Silicon Photo Multipliers (SiPM)

The HCAL prototype comprises 38 planes of scintillating detectors with 216 tiles in first 30 planes and 145 tiles in 8 last ones.

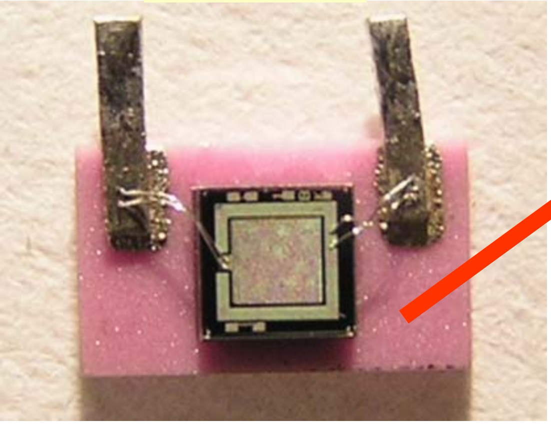




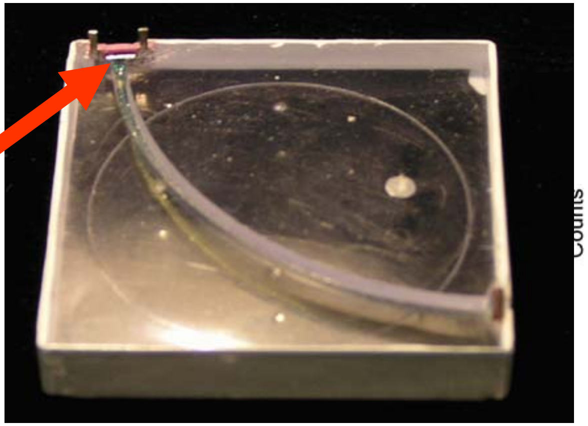
LAL 18 ch. SiPM FE chip

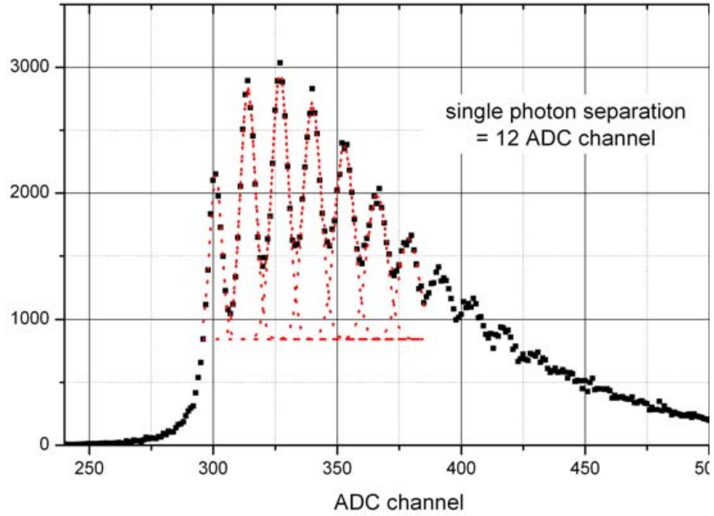
Light from a tile is read out via WLS fiber and SiPM

SiPM

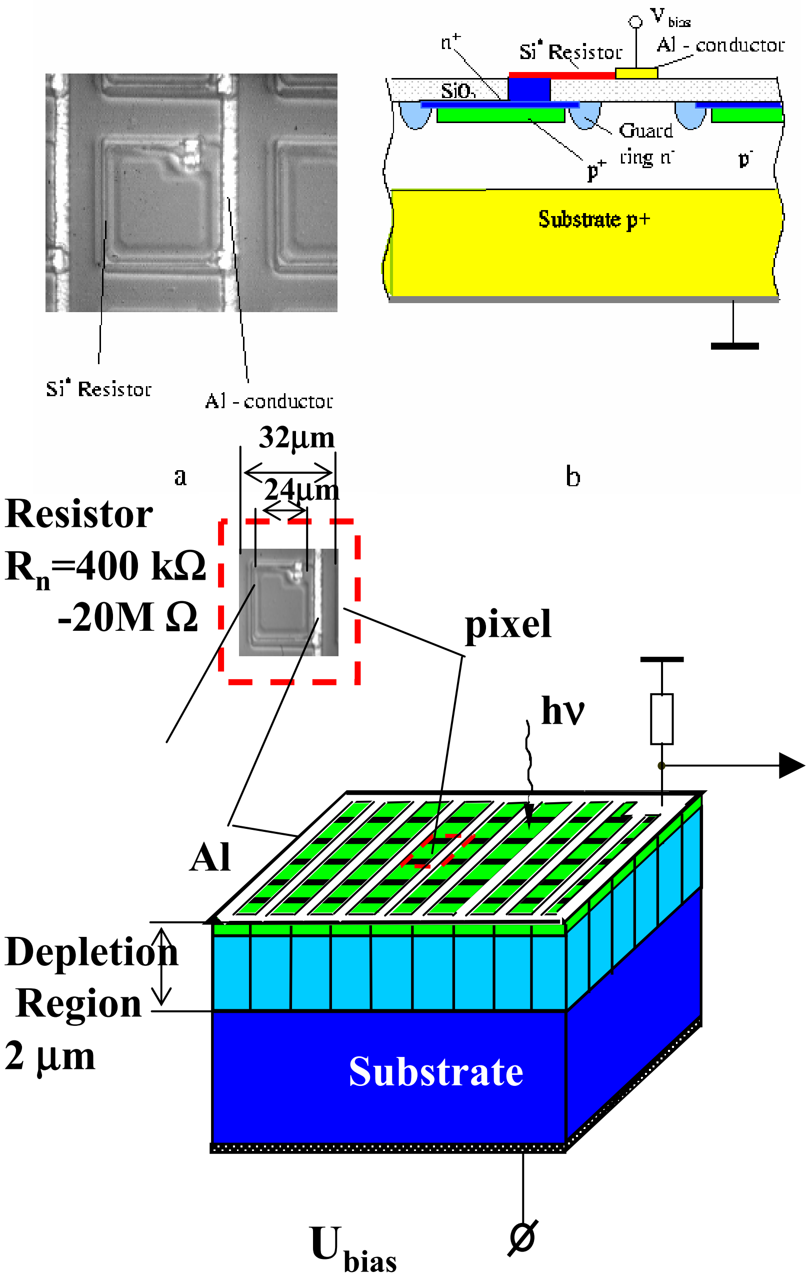


3x3 cm^2 tile with SiPM





SiPM (MEPhI-Pulsar) main characteristics



- 1156 pixels of $32\times32\mu m^2$ (actvive area 24x24)
- Working point: $V_{Bias} = V_{breakdown} + \Delta V \sim$ 50-60 V
  $\Delta V \sim$ 3V above breakdown voltage
- Each pixel behaves as a Geiger counter with $Q_{pixel} = \Delta V\, C_{pixel}$ with $C_{pixel} \sim 50fF$ ➔ $Q_{pixel} \sim 150fC = 10^6 e$

- Noise at 0.5 p.e. ~ 2MHz

- Optical inter-pixel cross -talk:
-due to photons from Geiger discharge initiated by one electron and collected on adjacent pixels
-Xtalk grows with ΔV. Typical value ~20%.

-PDE ~15% for Y11 spectrum

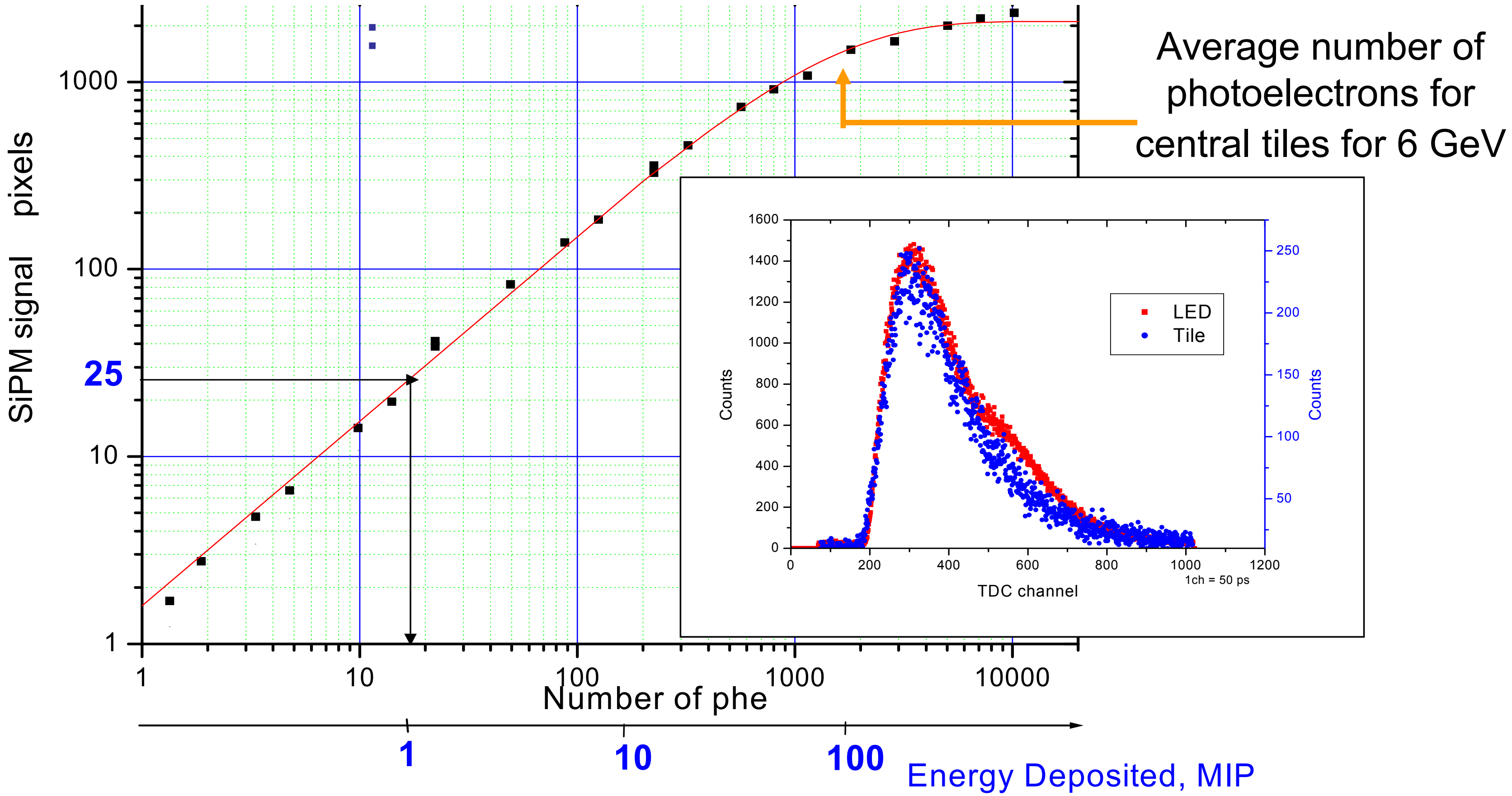
Insensitive to magnetic field (tested up to 4Tesla)

Very short Geiger discharge development < 500 ps

Pixel recovery time = $(C_{pixel} R_{pixel}) \sim 20$ ns (for small R)

Dynamic range ~ number of pixels (1156)➔ saturation

SiPM signal saturation due to finite number of SiPM pixels



Average number of photoelectrons for central tiles for 6 GeV

Very fast pixel recovery time ~ 20ns for R~0.5 MΩ

For large signals each pixel fires about 2 times during pulse from tile

➡ **Saturation curve depends on signal shape** ➡ **Problems in calibration**

➡ **Use large R> 2MΩ**

Selection of SiPMs

1. Long term stability test: ~48 hours at elevated HV (~+3V->5 μA)

Selection criteria: SiPM current < 5 μA

2. Tune of operation HV and saturation curve measurement with LED

Tune HV till number of pixels per MIP 14.25 < ***Npix*** < 15.75

Selection criteria:

SiPM gain ***G*** > $4*10^5$

Noise frequency at zero level $F_0 < 3$ MHz

Noise frequency at ½ MIP level $F_{1/2} < 3000$ Hz

Crosstalk < 0.35

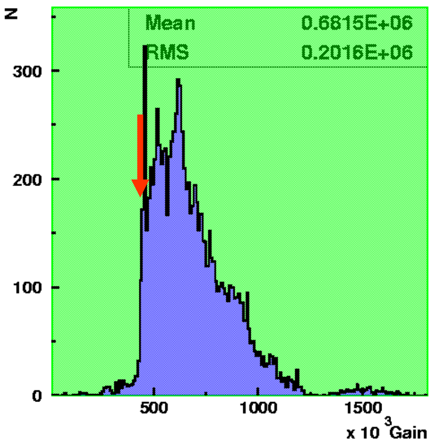
SiPM current $I < 2$ μA

RMS of multiple SiPM current measurements $RMS_I < 20$ nA

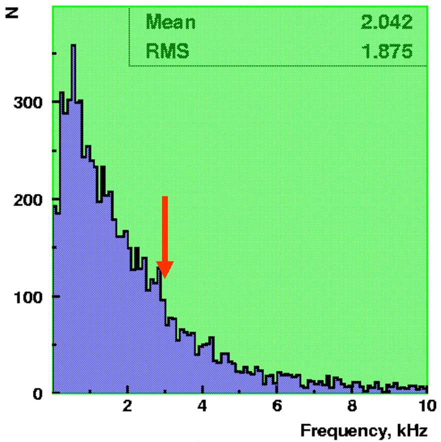
Number of pixels at maximal light (~200MIP) during measurement of saturation curve $N_{pix\ max} > 900$

3. Check Tile-WLS Fiber-SiPM system with Sr source

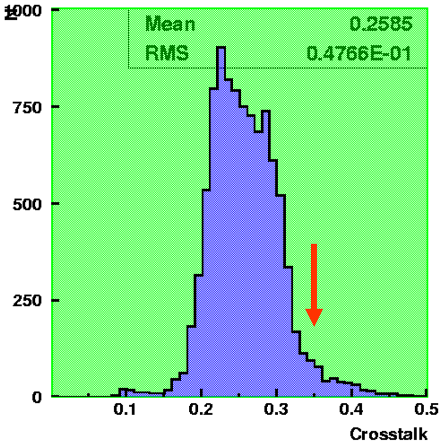
Parameters of ~ 10000 tested SiPM's



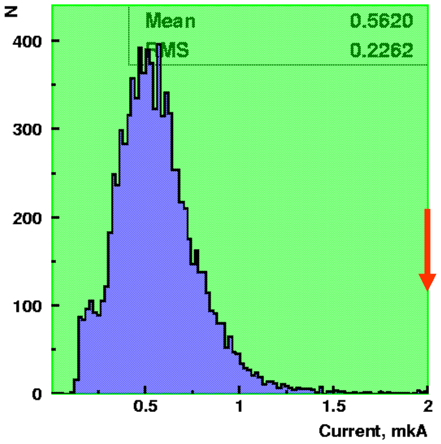
GAIN



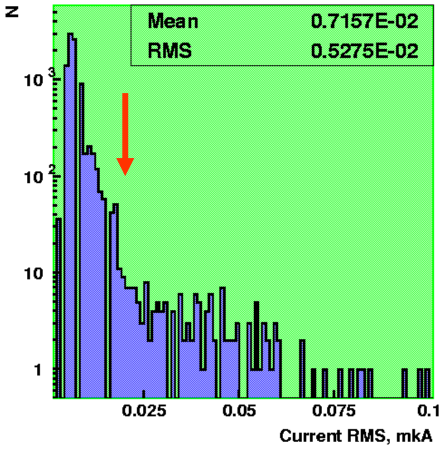
NOISE AT ½ MIP(7.5 pixels)



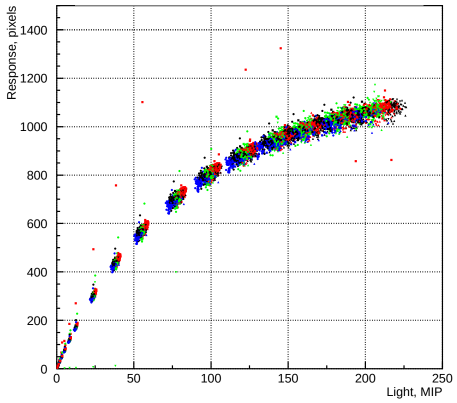
CROSS TALK



SIPM CURRENT

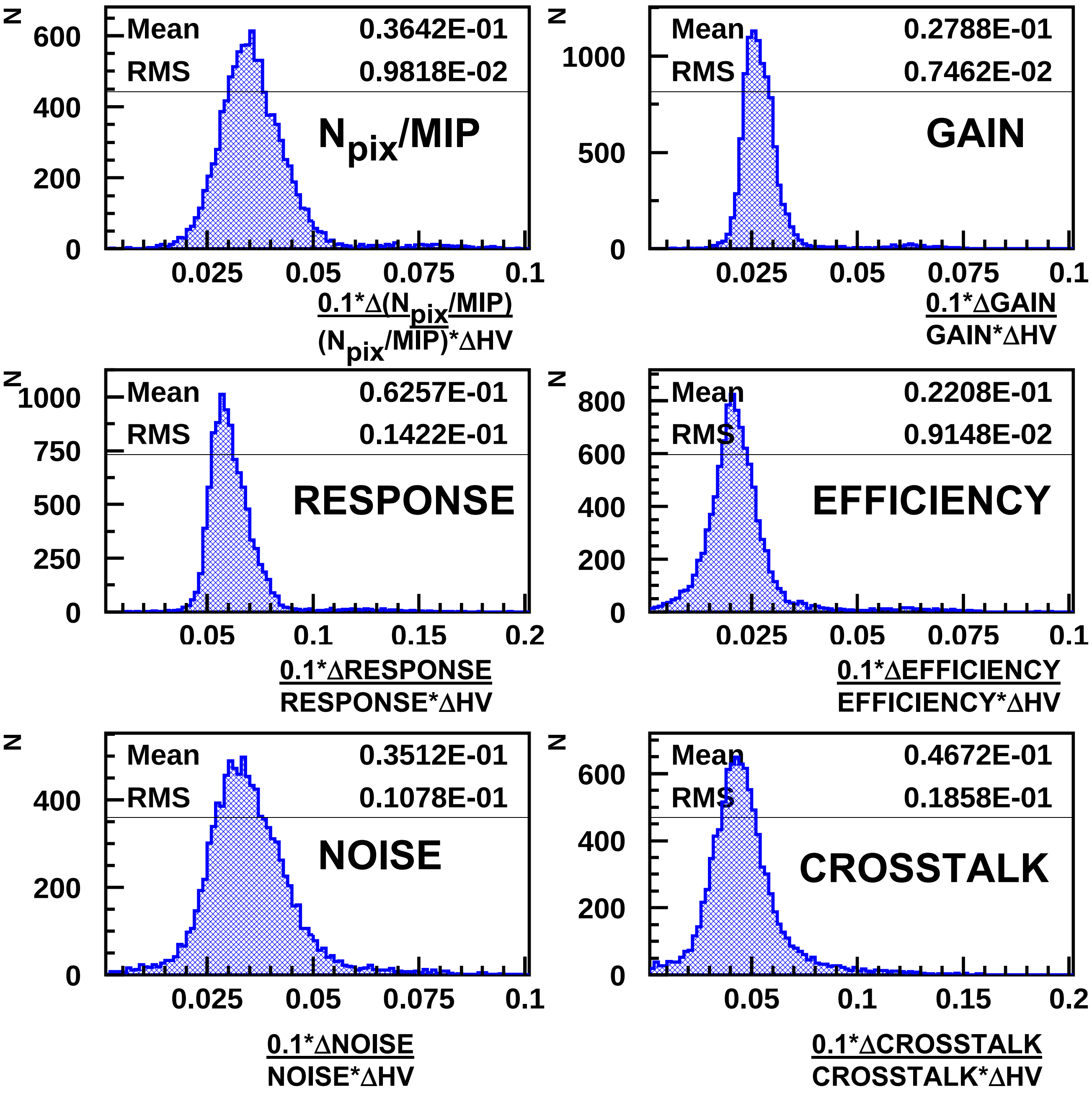


CURRENT STABILITY



SATURATION CURVE

SIPM PARAMETER VARIATION AT 0.1 V HV VARIATION

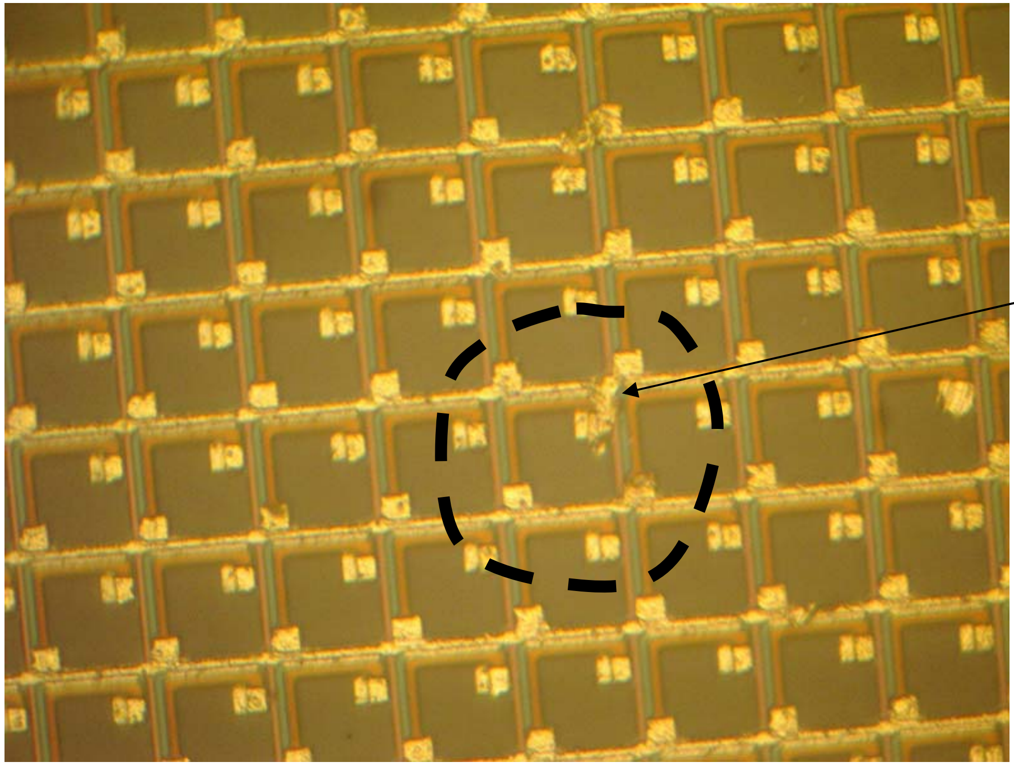


Some SiPMs demonstrated long discharges

SiPMs with LD were investigated under high gain microscope

The reason for LD were short circuits produced mainly by discharge between Al bus and polysilicon resistor (E~3V/3μm~10^4 V/cm)

SiPM 2634



Pixel with LD

Al short circuit due to point like defect

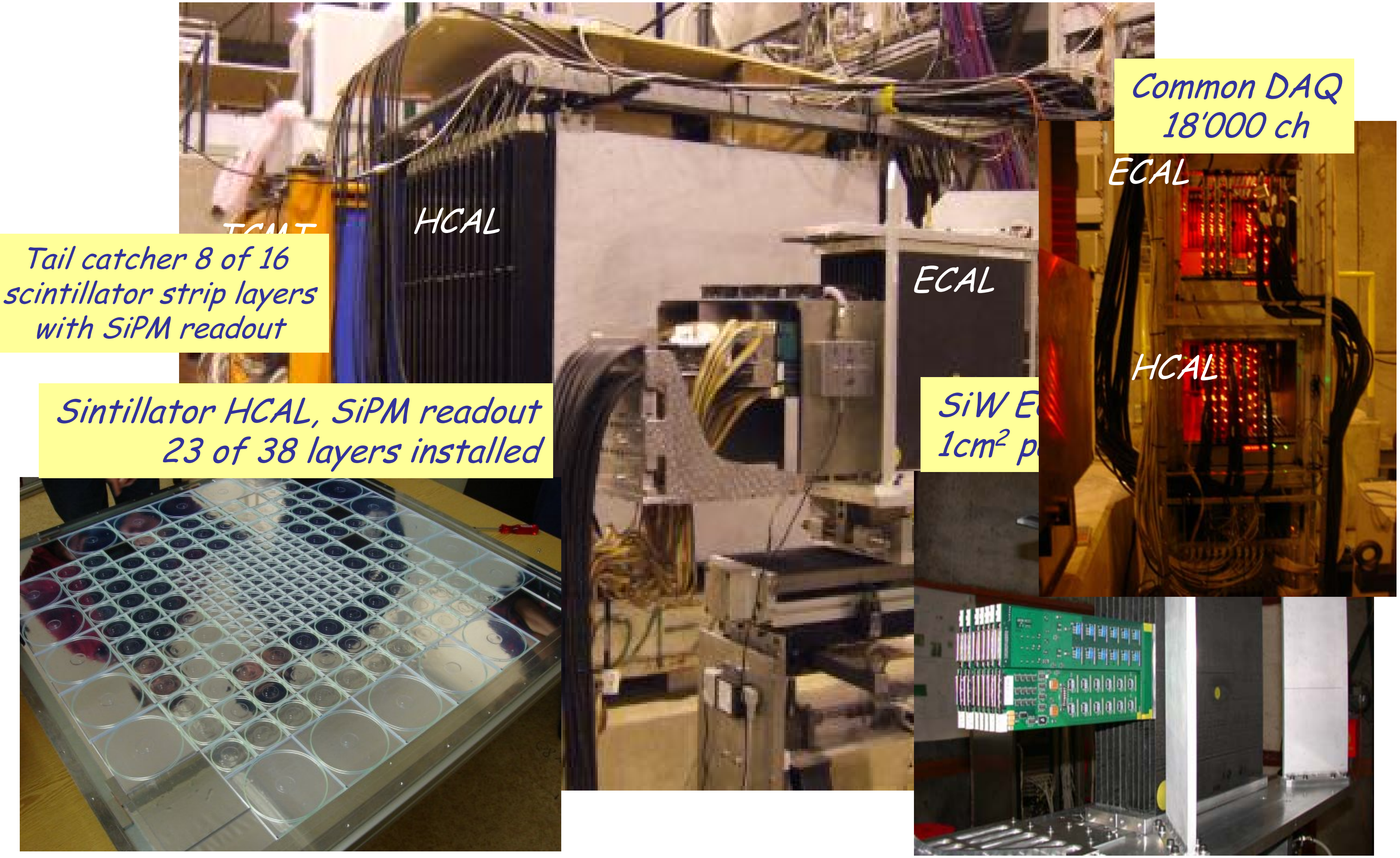
Pixel geometry will be improved in the next SiPM version

For the present prototype elevated HV test was introduced to reject problematic SiPMs

This test isn't perfect . Still ~1% of channels in planes 3-23 demonstrate long discharges

HCAL, ECAL, and TC have been tested last year at CERN

Set-up at SPS H6b



Common DAQ
18'000 ch

Tail catcher 8 of 16
scintillator strip layers
with SiPM readout

Sintillator HCAL, SiPM readout
23 of 38 layers installed

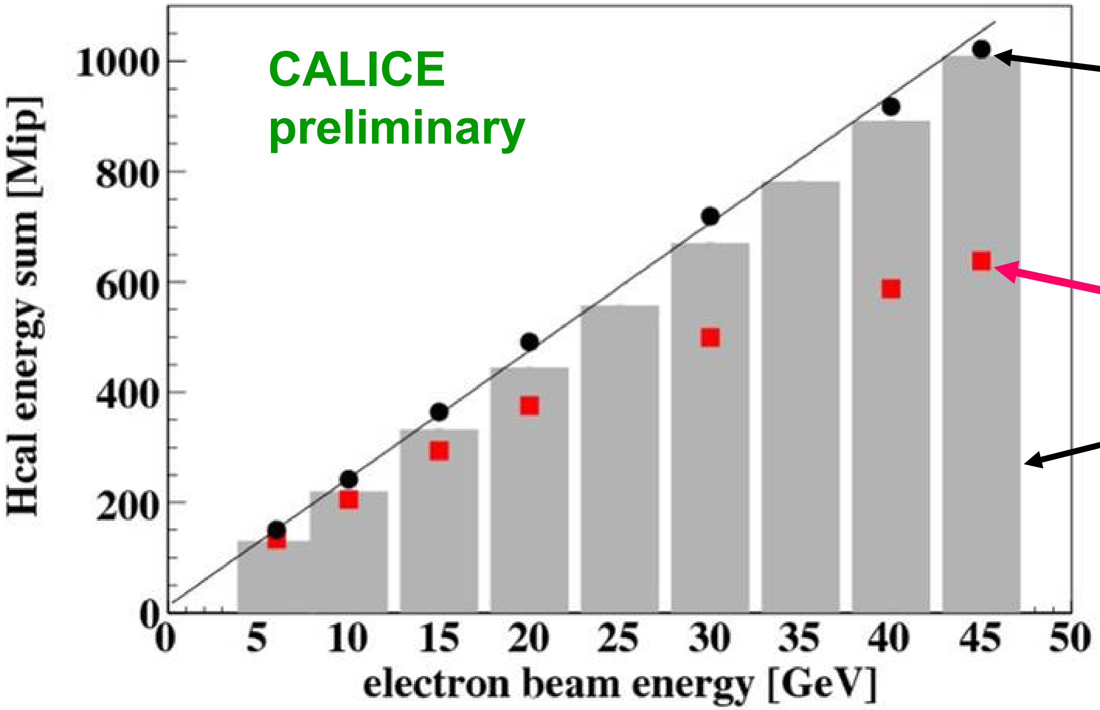
SiW E
1cm^2 p

Operational experience with HCAL

HCAL was operated practically without problems at CERN during 15 weeks initially with 15 planes and then with 23 planes. 38 planes will be tested in July

In planes 3-23 (which were produced after observation of long discharge problem)
~98% of channels are good
~1% are dead (because of problems with SiPM soldering – improves with time)
~1% demonstrate long discharges (SiPM selection procedure was not perfect)

Good channels were calibrated with muons and corrected for non linear SiPM response

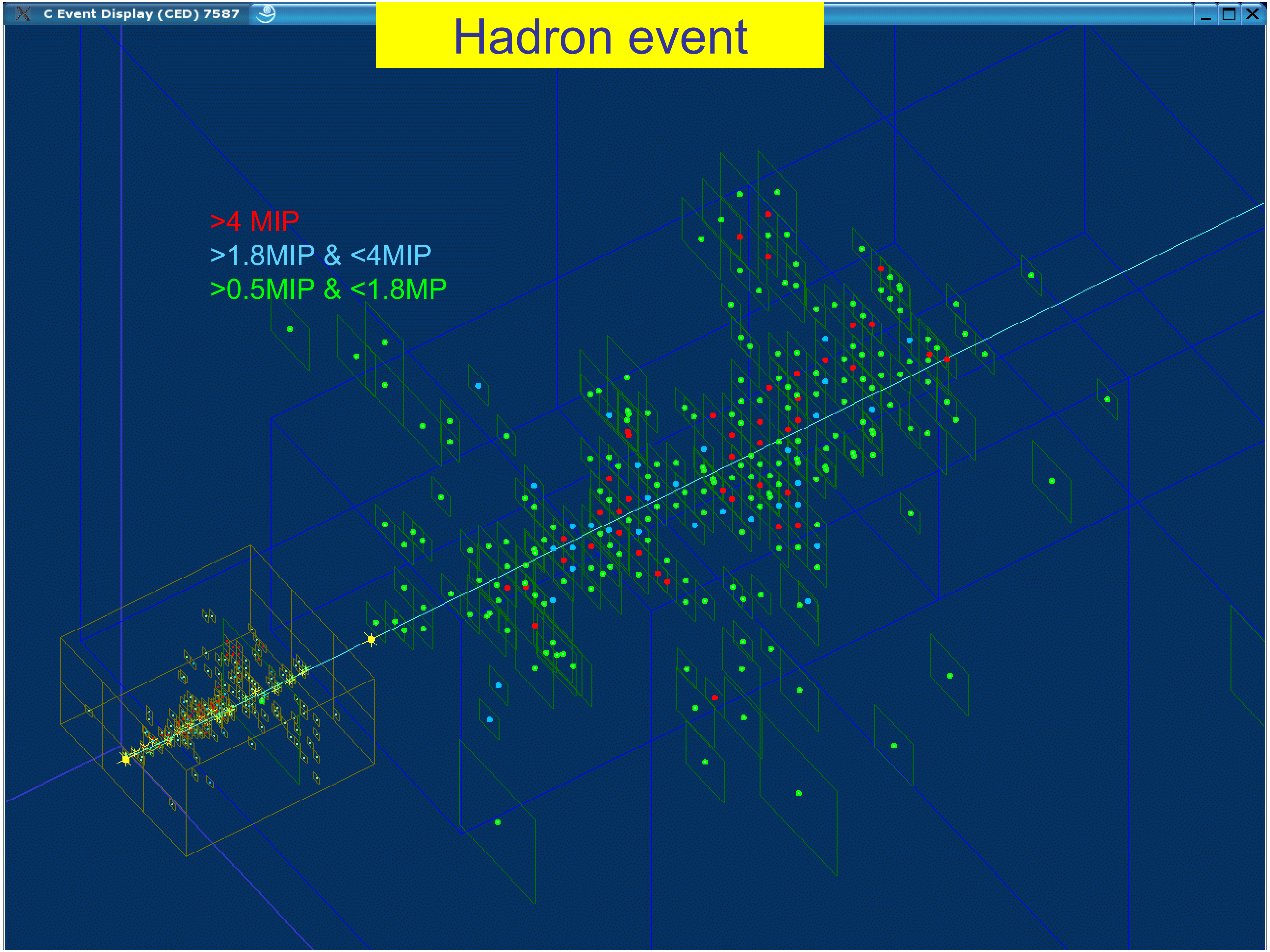


HCAL response after correction is perfectly linear for electrons up to 45 GeV

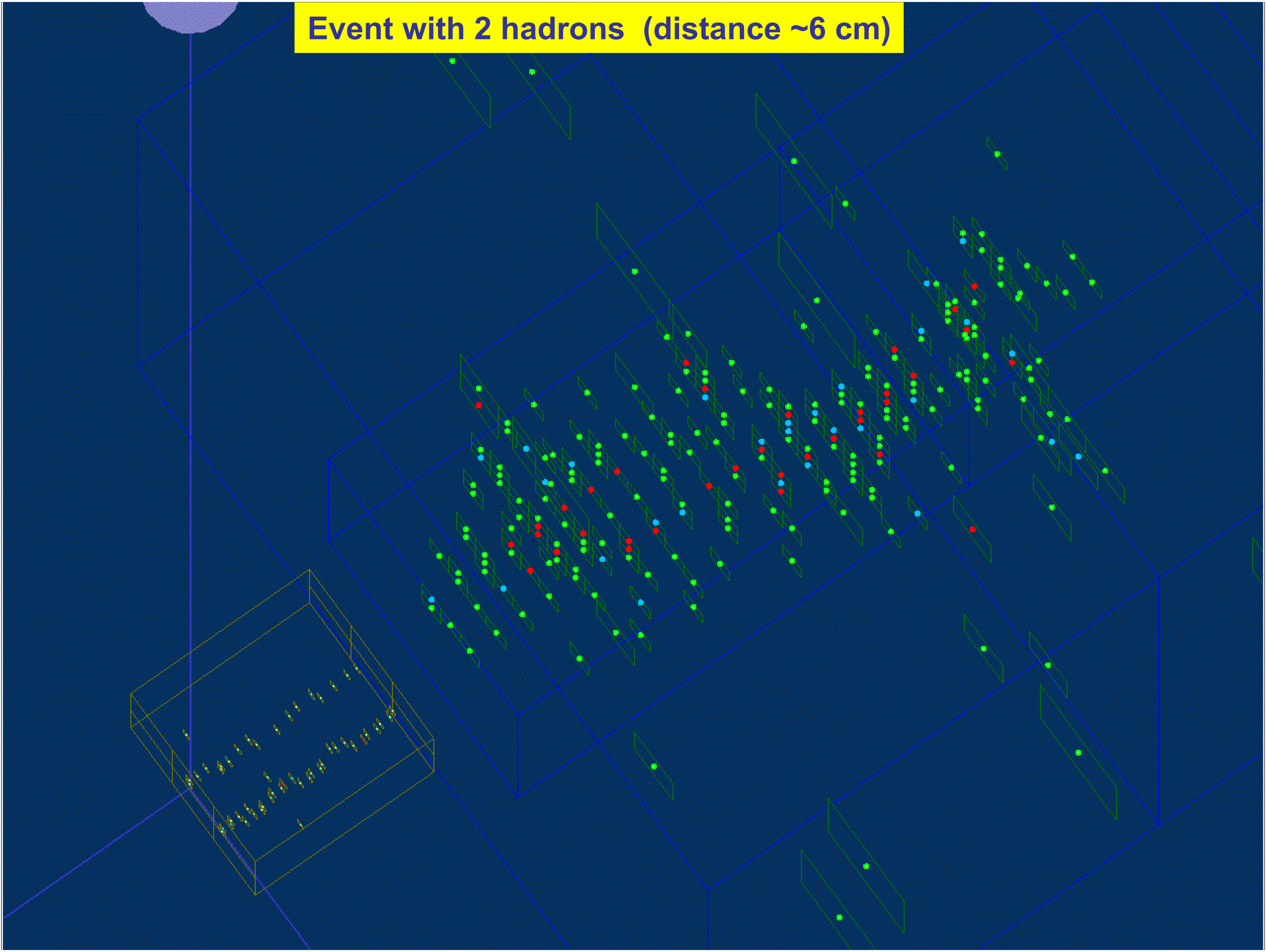
Response before correction

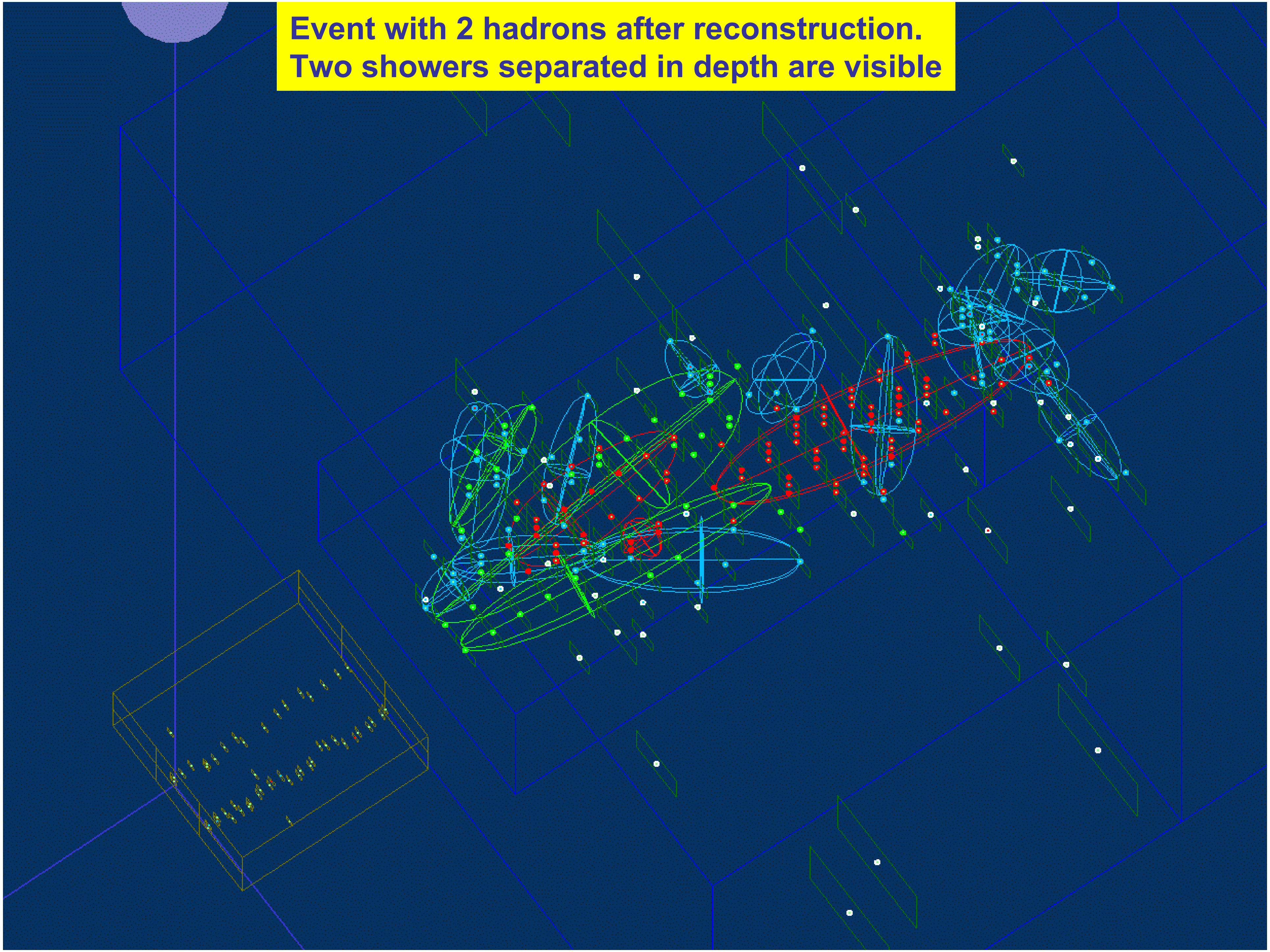
MC

Hadron event



Event with 2 hadrons (distance ~6 cm)



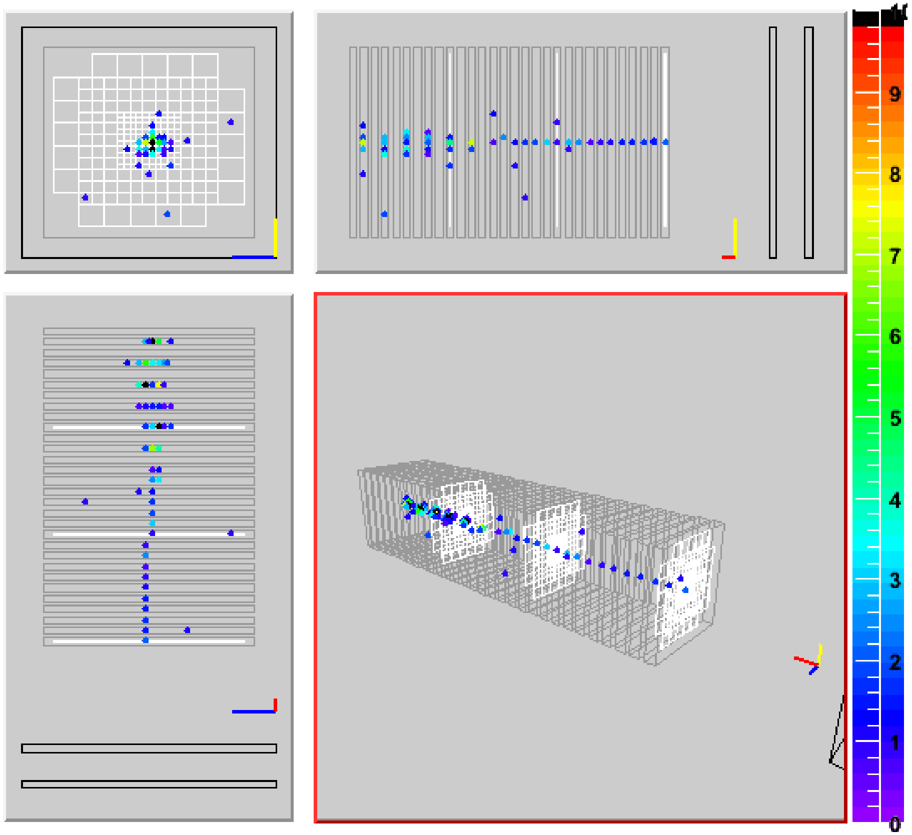


Event with 2 hadrons after reconstruction.
Two showers separated in depth are visible

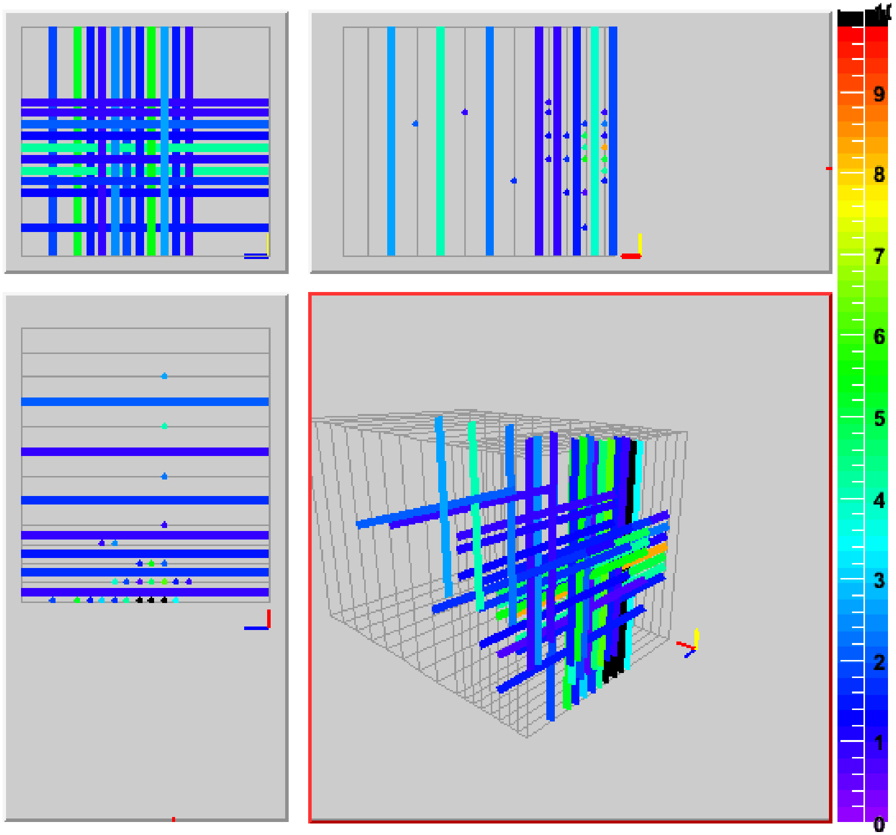
Example pion event display

40GeV/c pion
with CALICE online analysis software

HCAL



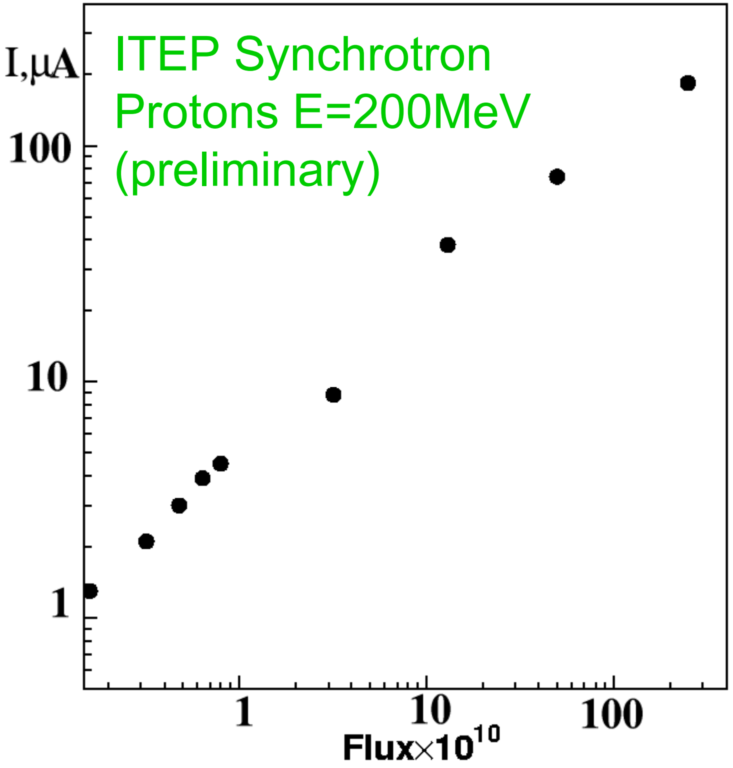
TCMT



Late shower in HCAL

TCMT clearly needed to contain shower

Radiation damage measurements



Dark current increases linearly with flux Φ as in other Si devices:

Δ I=α Φ Veff Gain, where $\alpha = 6\times10^{-17}$A /cm

Veff ~ 0.004mm^3 determined from observed **ΔI**
looks a bit too high
(since it includes SiPM efficiency)
but not completely unreasonable

Since initial SiPM resolution of ~0.15 p.e. is much better than in other Si detectors it suffers sooner:
After **Φ**~10^{10} individual p.e. signals are smeared out

However MIP signal are seen even after **Φ**~10^{11}/cm^2

At ILC neutron flux is much smaller than 10^{10}/cm^2 except a small area (R<30cm) around beam pipe

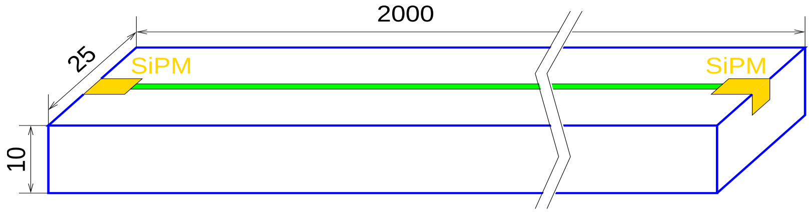
→ Radiation hardness of SiPM is sufficient for HCAL

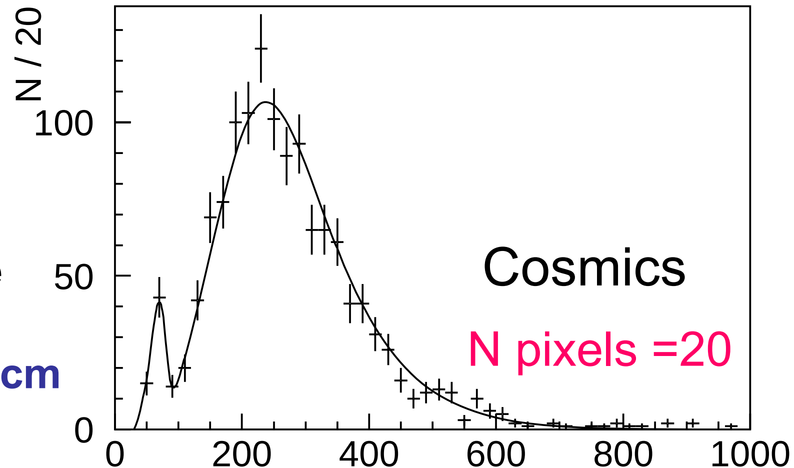
First Conclusions

Scintillator tile calorimeter with WLSF and SiPM readout is a viable option for ILC HCAL but industrialization is needed for several hundred times larger system

Scintillator strips with WLSF and SiPM readout can be used for ILC muon system

Tests of 2 m long strip at ITEP





Position along strip can be determined from time measurements:

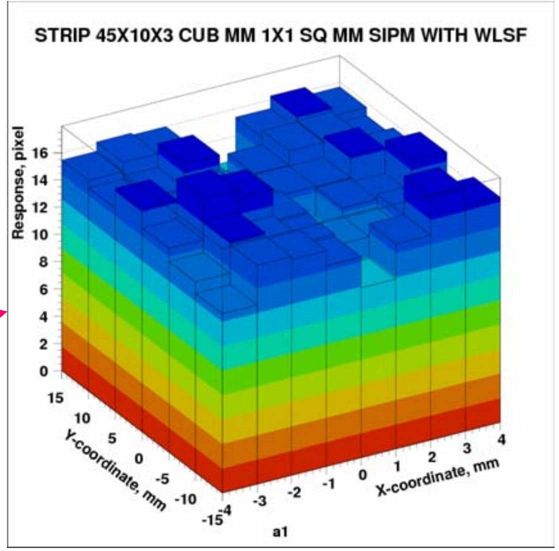
Achieved time resolution ΔT~2ns leads to ΔX~25cm

More experience will be gained from TCMT tests

Thin scint. strips with WLSF+SiPM readout provide sufficient light and uniformity (~6%) for last layers of EM calorimeter

(approach is extensively tested by Japanese groups)

Uniformity measurements for 3x10x45 mm^3 strip with WLSF and SiPM readout

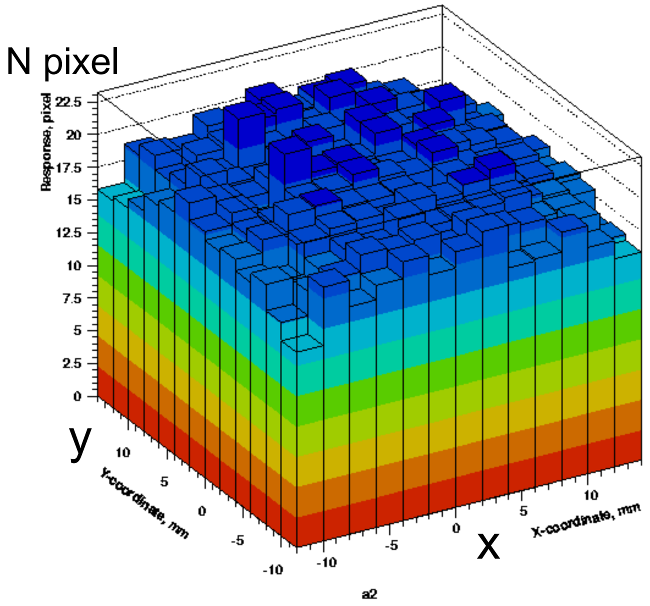


Tile thickness can be reduced to 3 mm (saves a lot of money)

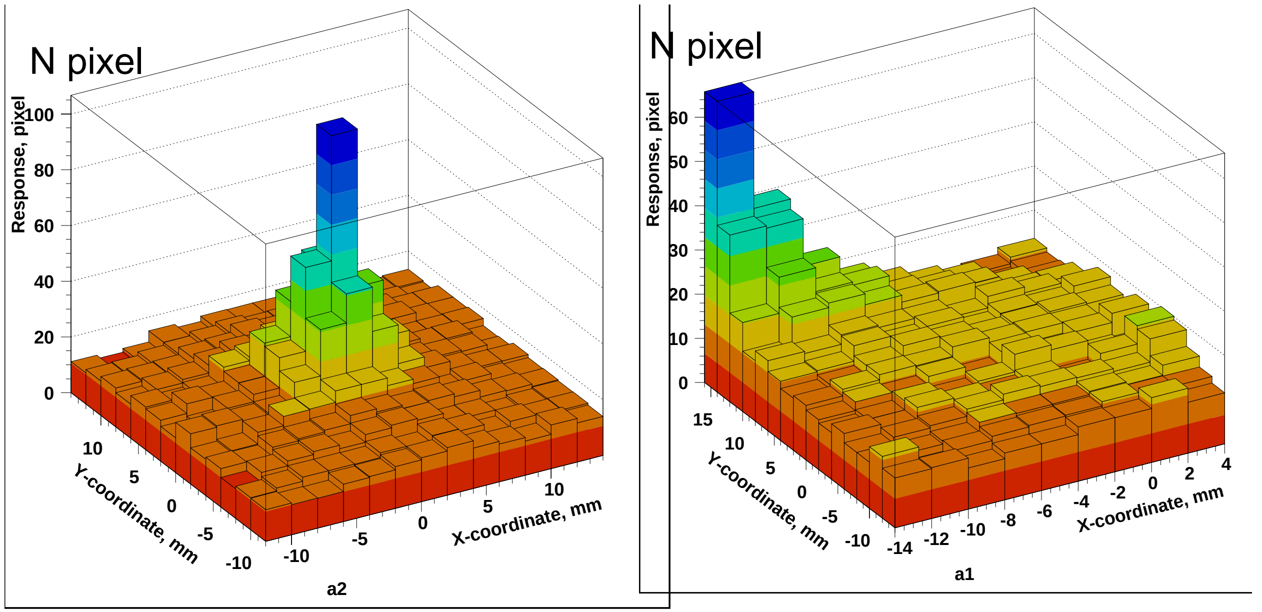
Response uniformity is good for tiles with WLS fibers even for thin tiles and problematic for direct SiPM coupling which is easier for fabrication

Uniformity measurements of 30x30x3mm^3 tiles at ITEP synchrotron

Arch fiber&SiPM 1.5MIP



Direct coupling of 1764 pixel 2x2mm^2 blue MRS APD



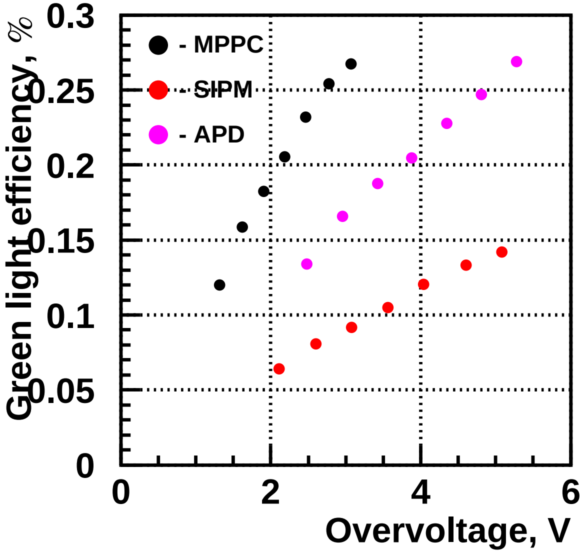
Problems with direct coupling will be more severe for larger size tiles

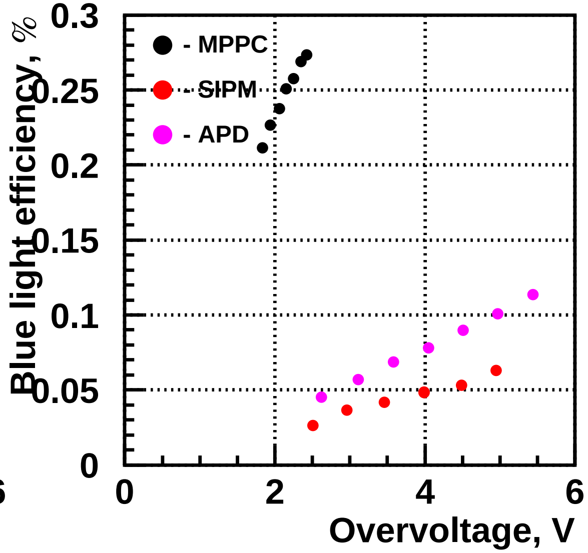
Light yield is sufficient for 3mm thick tiles with glued WLSF and SiPM (~14pix./MIP) and larger area SiPMs (3x3mm^2) or MRS APD (2x2mm^2 blue extended) but noise is too high in these detectors to resolve individual p.e. – bad for calibration

Recently low noise blue sensitive MPPC with high PDE were developed by HPK

Comparison of different Multipixel Geiger Photo Diods (MGPD)

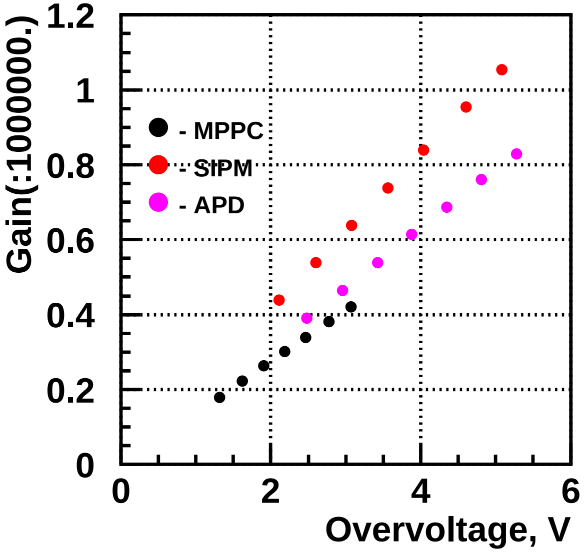
(MPPC(1600 pix), SiPM (1156 pix), MRS APD(656pix))

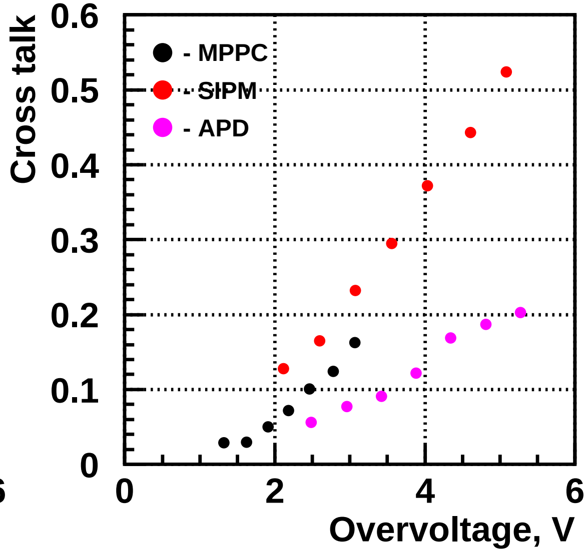


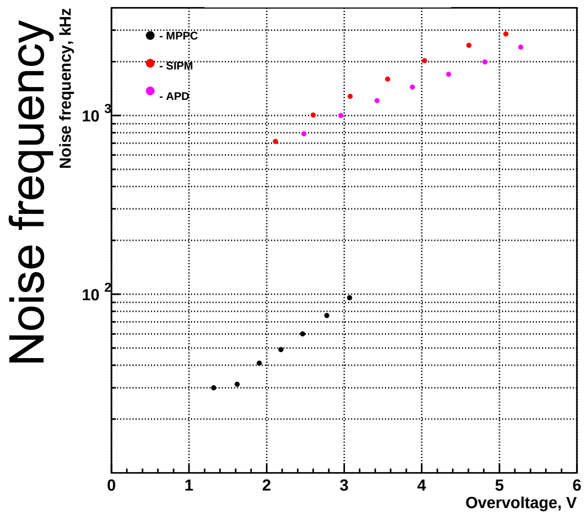


MGPD were illuminated with Y11 (green) and scintillator (blue) light Efficiency was normalized to MPPC one

MRS APD with 25% larger efficiency already exist.



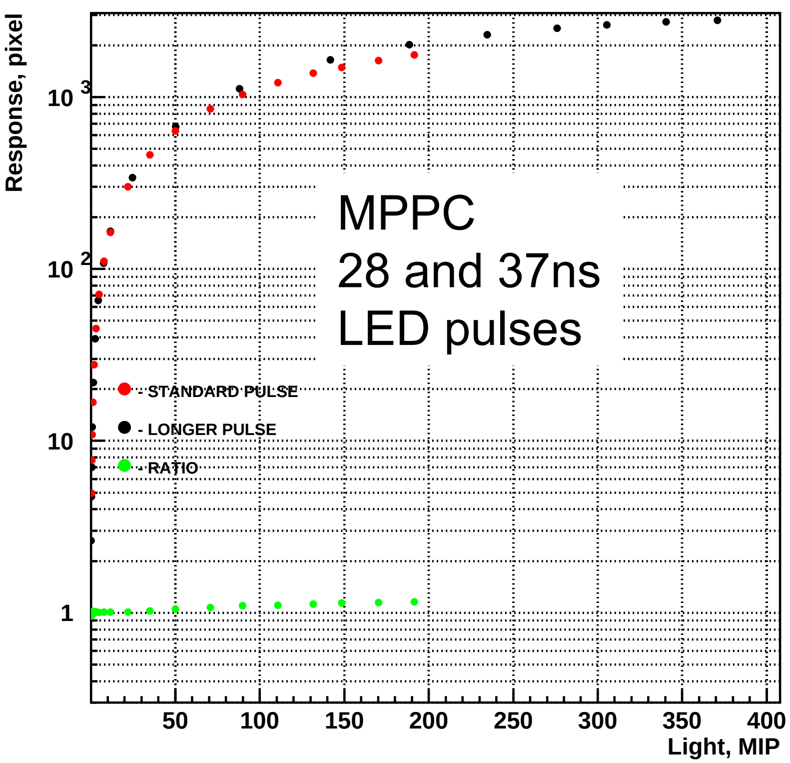


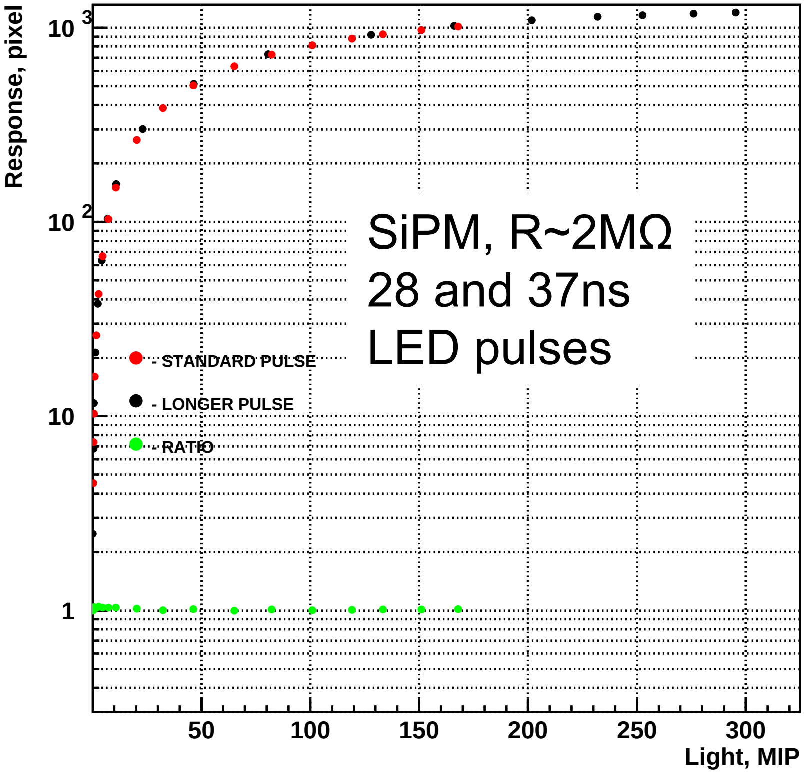


Measurements at DESY and ITEP give 7-9 p.e./MIP for direct MPPC (1600pix) readout of 5mm thick 30x30mm^2 tiles and ~5p.e./MIP for 3mm thick tile

MPPC(1600pix) do not provide enough p.e. for direct readout of 3x30x30mm^3 tiles
Photo-electron yield is even smaller for larger tiles (~2p.e. for 60x60x5mm^3 tile)

MPPC saturation curve dependence on pulse length create problems for calibration





Larger size MPPC could be adequate for direct tile readout since noise is not a limiting factor. Better scintillator and gluing could also help

However long term stability and radiation hardness should be demonstrated

Summary

ILC HCAL prototype is the first (and successful!) large scale (~10^4) application of novel photo-detectors - SiPMs

Scintillator tile calorimeter with WLSF and SiPM readout is a viable option for ILC for analog and semi-digital approaches, but a lot of industrialization is required
The same technique can be used for ILC muon system and
last layers of ECAL

Possibility to use direct MGPD coupling is still to be demonstrated (uniformity and p.e. yield)

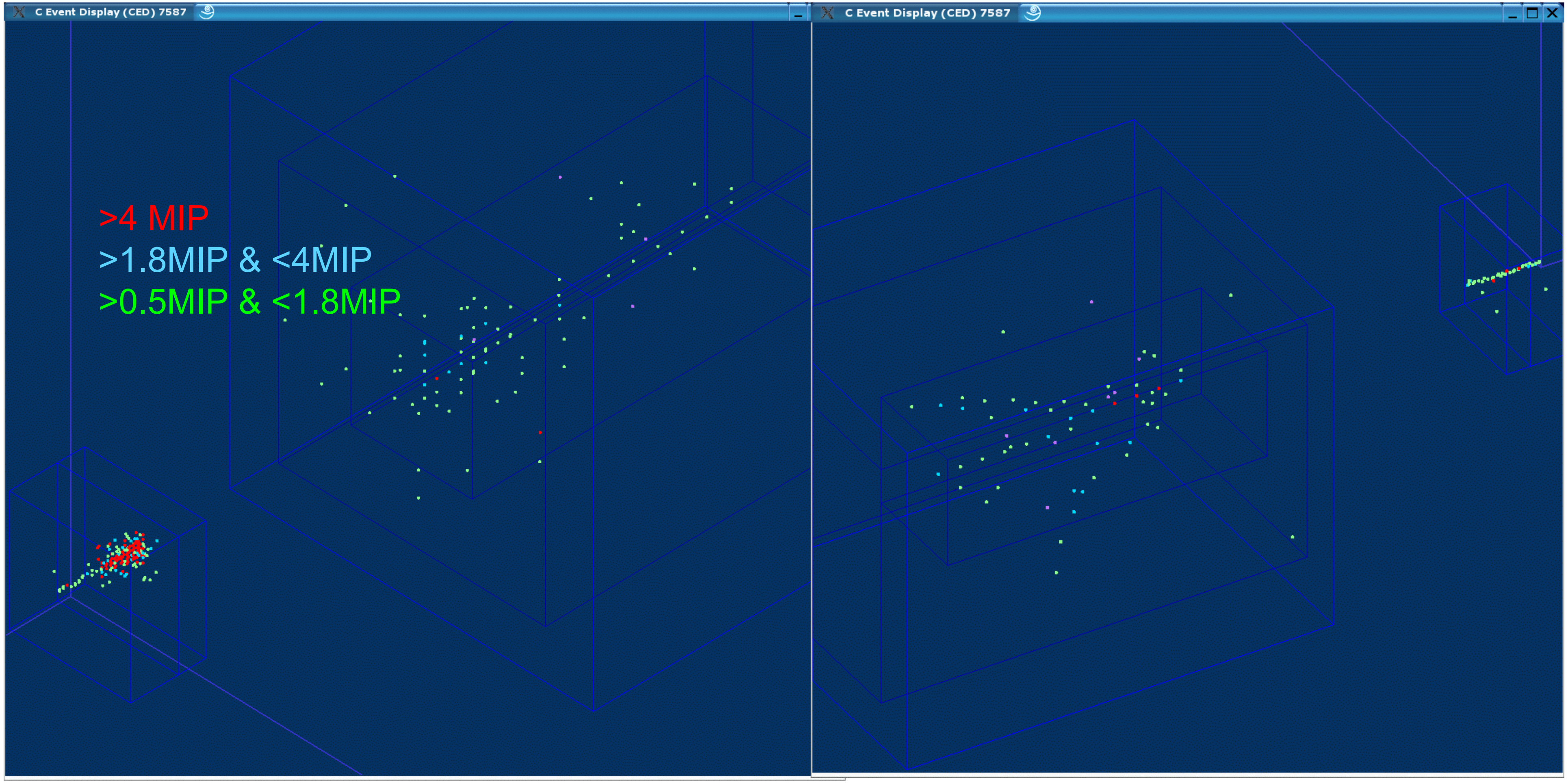
The field is developing very fast. Photo-detector properties improve every year.
The final choice of the Photo-detector depends on the overall optimization

Selection between Analog, Digital or Semi-Digital approaches depends on the outcome of the test program at CERN and FNAL

A more realistic and scalable prototype with 3mm thick tiles and integrated electronics is being designed by CALICE and partially supported by EUDET

Backup slides

Hadron events

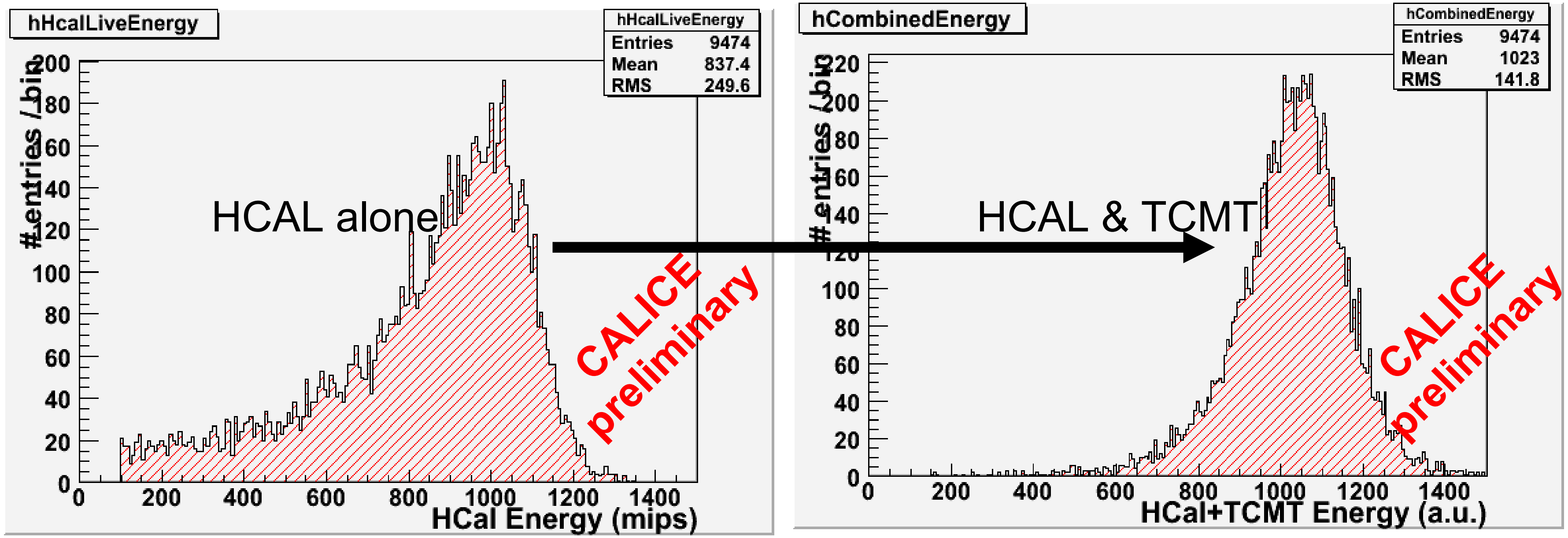


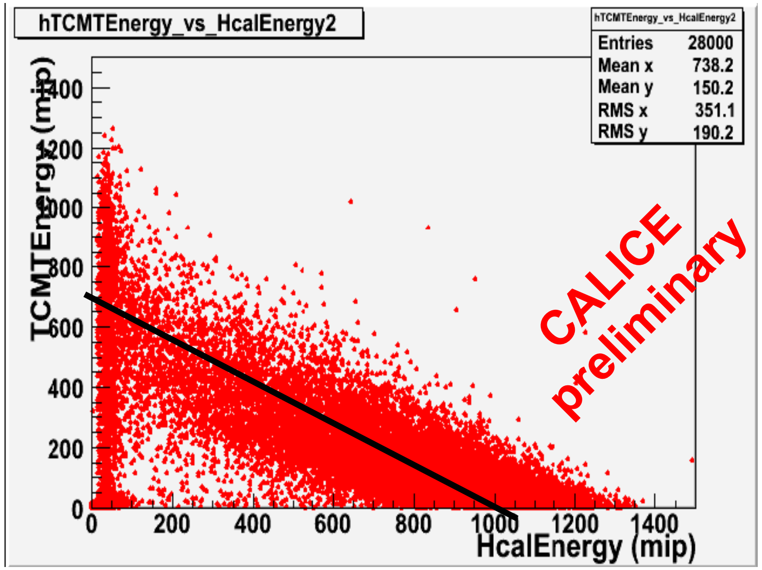
>4 MIP

>1.8MIP & <4MIP

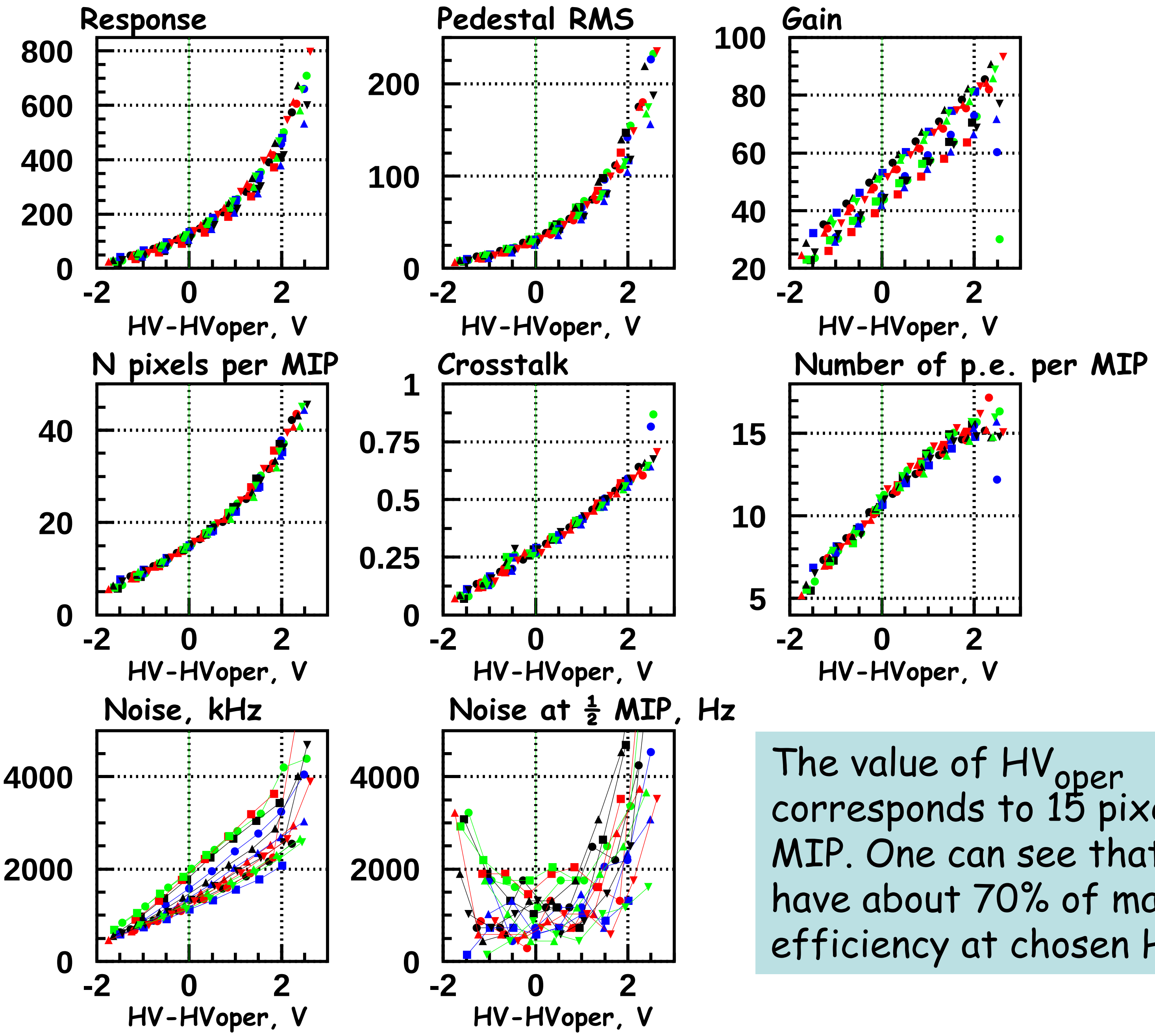
>0.5MIP & <1.8MIP

Energy Response to 80GeV Pion Beam





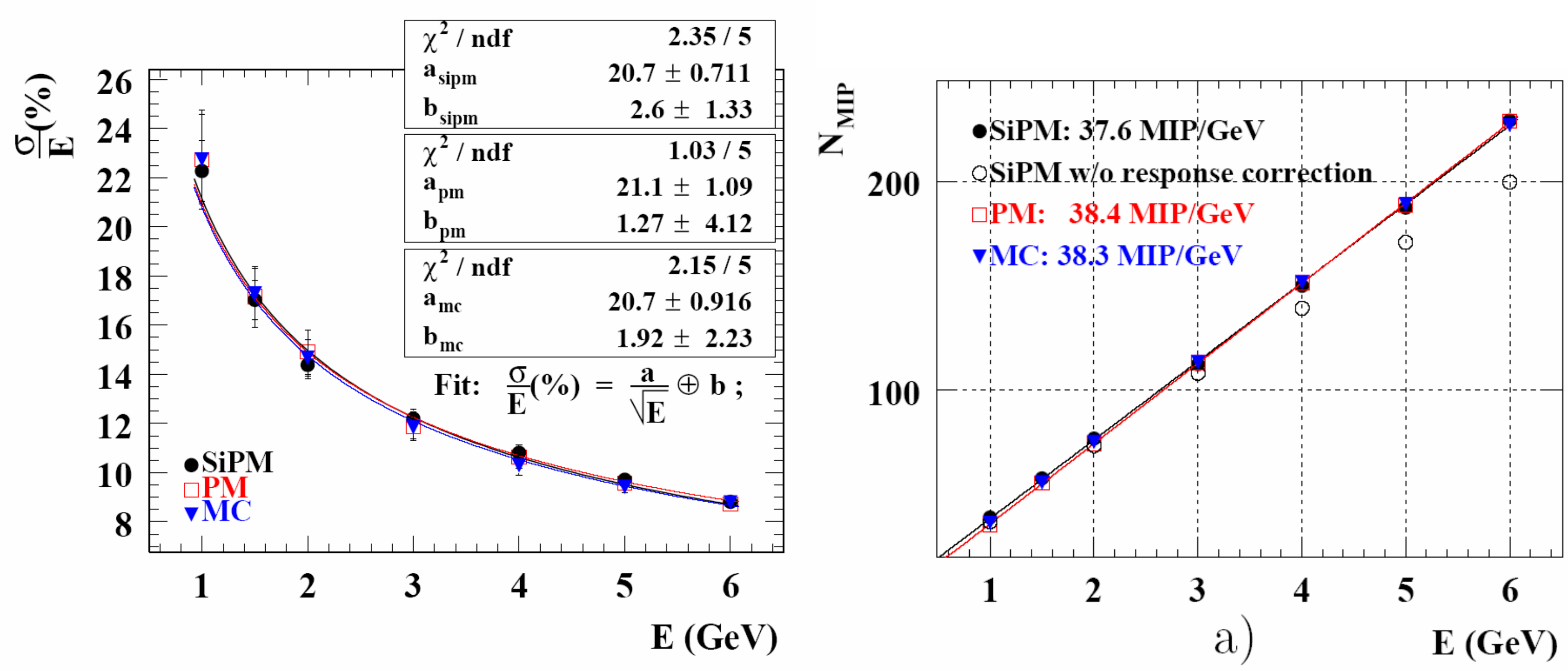
- **Different sampling fractions corrected with constant factor between HCAL and TCMT.**
- **The MIP-calibrated energy is summed on event-basis.**
- **Resolution improves by a factor of 2**
- **Very preliminary, done with online analysis package**



The value of HV_{oper} corresponds to 15 pixels per MIP. One can see that we have about 70% of maximal efficiency at chosen HV_{oper}.

MINICAL tests with electron beam

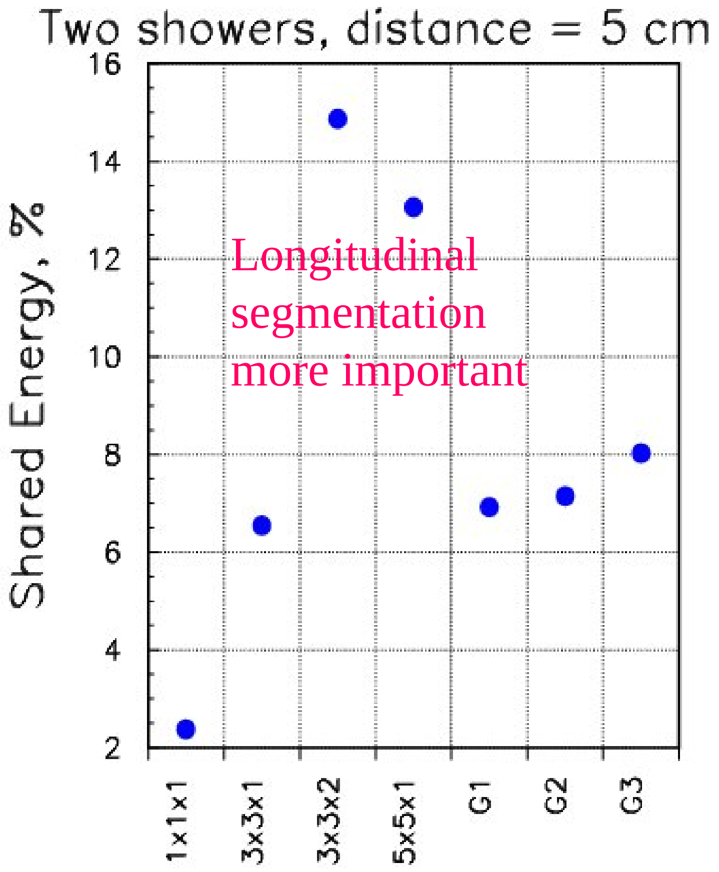
Measurement of electron energy with HADRON CALORIMETER ⇒ resolution modest



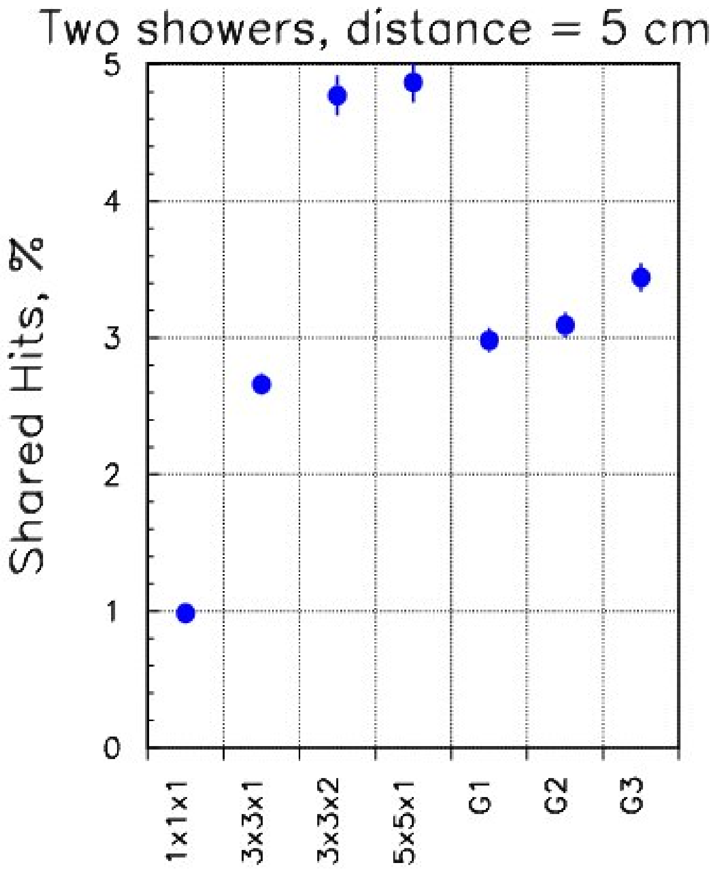
- ➔ Very good agreement between SiPM, MAPMT, APD(not shown) and MC in the whole range 1 - 6 GeV
- ➔ SIPM non-linearity can be corrected even for dense e/m showers for each tile and does not deteriorate resolution
- ➔ Possibility to observe peaks for different number of p.e. crucial for calibration
- ➔ Low sensitivity to constant term due to limited energy range

Tile Size Optimization

Separability of showers as main criteria for optimization



Longitudinal
segmentation
more important



⇑

Intrinsic property of PPT independent from clustering algorithm

The Particle Flow Concept

What is the best way to measure the energy of a jet?

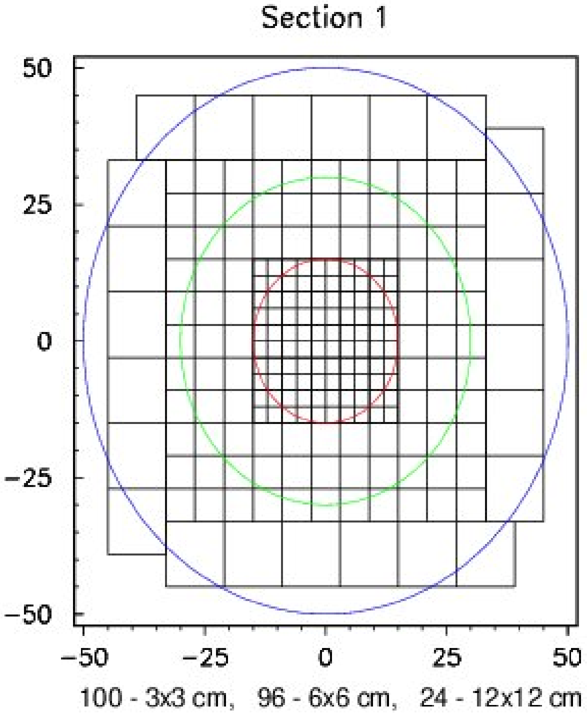
Classical: purely calorimetric
typically 30% e.m. and 70% had. energy
for $\Delta E/E(em) = 10\%/\sqrt{E}$ and $\Delta E/E(had) = 50\%/\sqrt{E}$
→ $\Delta E/E(jet) \sim 45\%/\sqrt{E}$

PFlow: combine tracking and calorimetry
typically 60% charged, 30% em(neut), 10% had(neut)
need to separate charged from neutral in calorimeter!
momentum resolution negligible at ILC energies
→ $\Delta E/E(jet) \sim 20\%/\sqrt{E}$ in principle (for ideal separation)
→ $\Delta E/E(jet) \sim 30\%/\sqrt{E}$ as a realistic goal

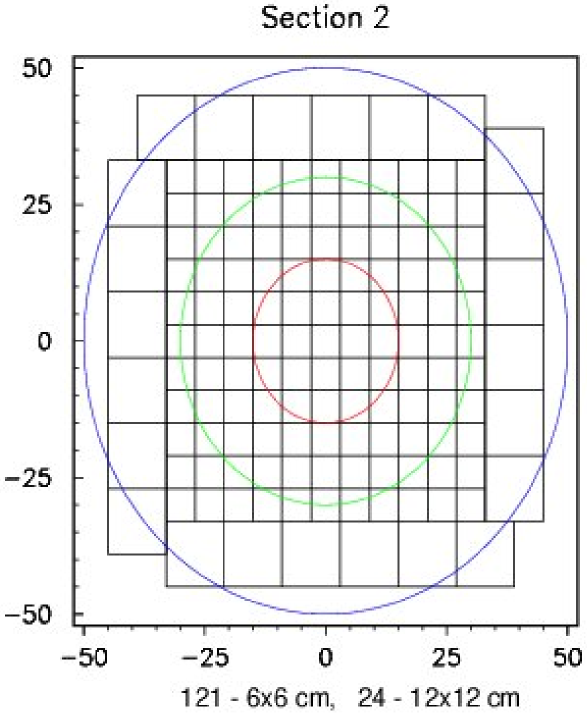
PFlow has further advantages: tau reconstruction
leptons in jets
multi-jet separation (jet algorithms…)

Prototype geometries

3,6,12 cm tiles for flexibility

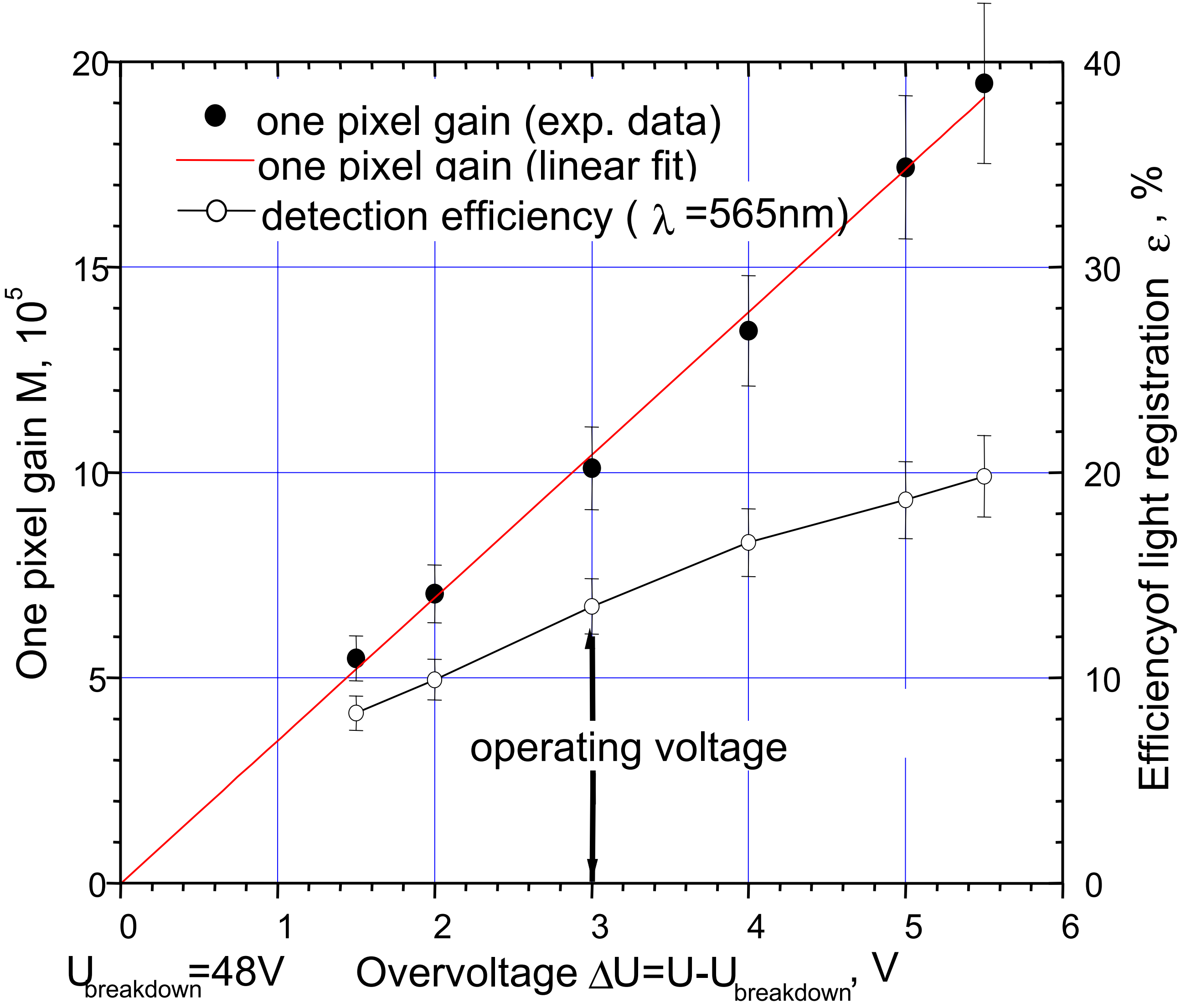


100 - 3x3 cm,   96 - 6x6 cm,   24 - 12x12 cm



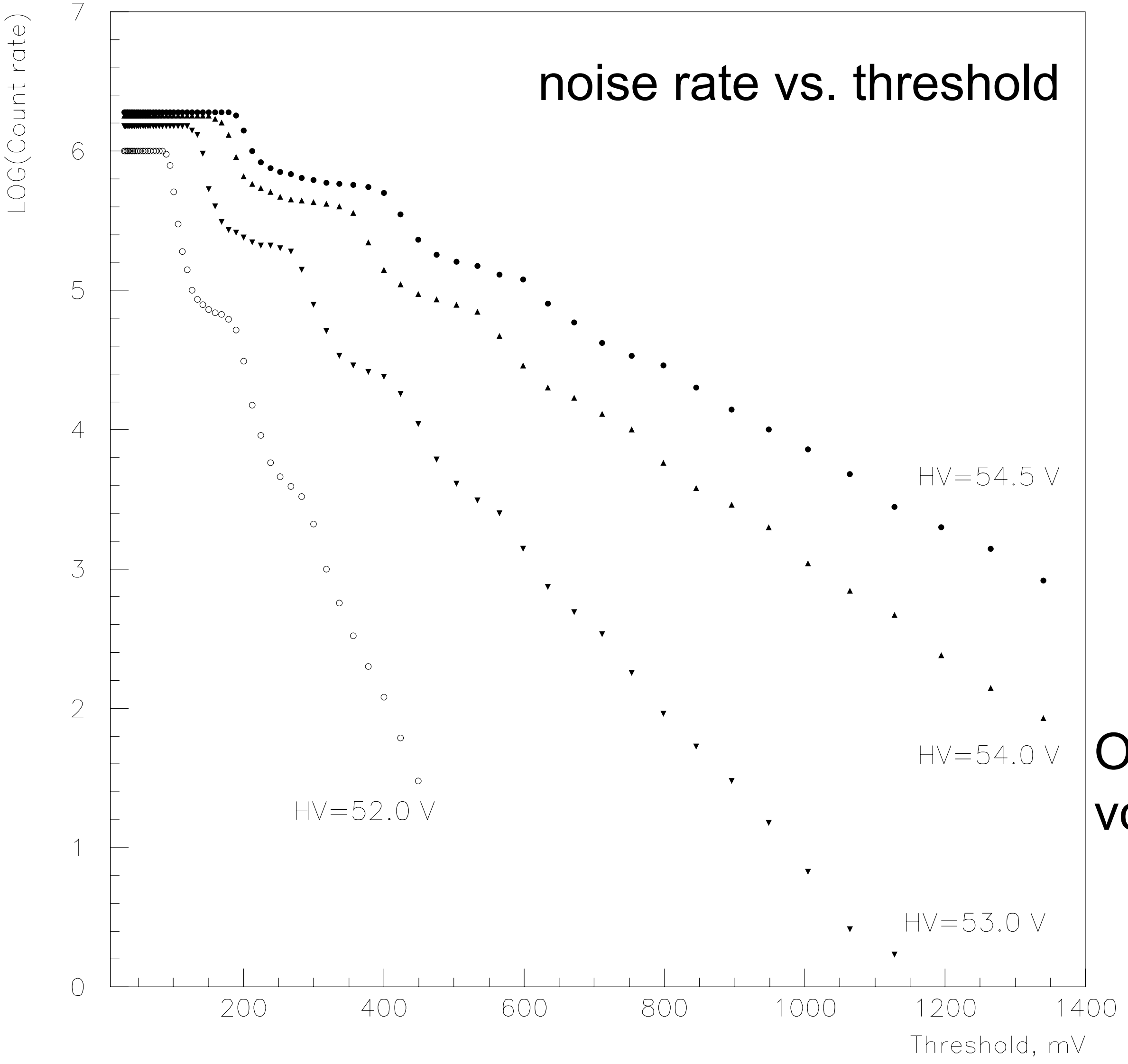
121 - 6x6 cm,   24 - 12x12 cm

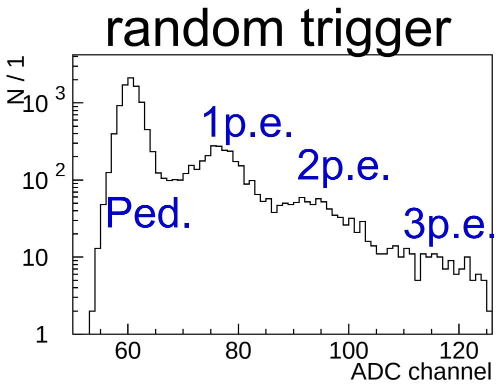
Geometry ID	Layers Section 1	Layers Section 2	Number of tiles
G1	1 - 30	31 - 39	7905
G2	1 - 26	27 - 39	7605
G3	1 - 20	21 - 39	7155



Photon detection efficiency $\varepsilon = QE \cdot \varepsilon_{geom}$

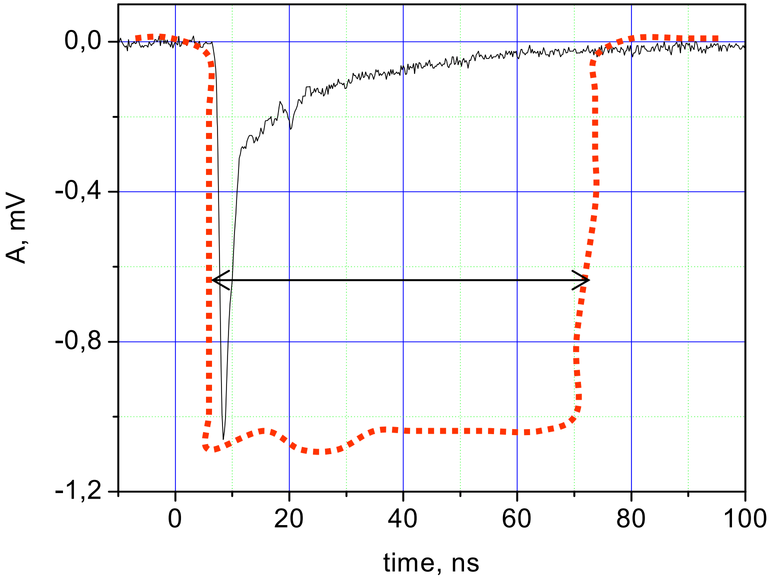
SiPM Noise





1p.e. noise rate ~2MHz.
threshold 3.5p.e. ~10kHz
threshold 6p.e. ~1kHz

Optimization of operating voltage depends on application



Random pulse length strongly increases with increasing of overvoltage

ΔV=Vapplied - Vbreakdown