Uso di fotomoltiplicatori al silicio in calorimetria adronica.

- *Cenni di calorimetria (adronica)*
  - *Principali problemi*
  - *Possibili soluzioni*
- *Ruolo dei SiPM in calorimetria (adronica)*
- *Metodi di compensazione*
  - *Prospettive*
- *Un esempio concreto: CMS HCAL*

Aldo Penzo, 16 Aprile 2013,

Lezione alla V Scuola Nazionale
"Rivelatori ed Elettronica per Fisica delle Alte Energie,
Astrofisica, Applicazioni Spaziali e Fisica Medica",
15-19 Aprile 2013, Laboratori Nazionali INFN di Legnaro

Il ruolo dei SiPM in Applicazioni Calorimetriche

Nella calorimetria adronica, le tendenze recenti danno risalto al ruolo di nuovi materiali attivi e di fotorivelatori recentemente sviluppati, al fine di ottenere una miglior risposta in energia mediante meccanismi di compensazione.

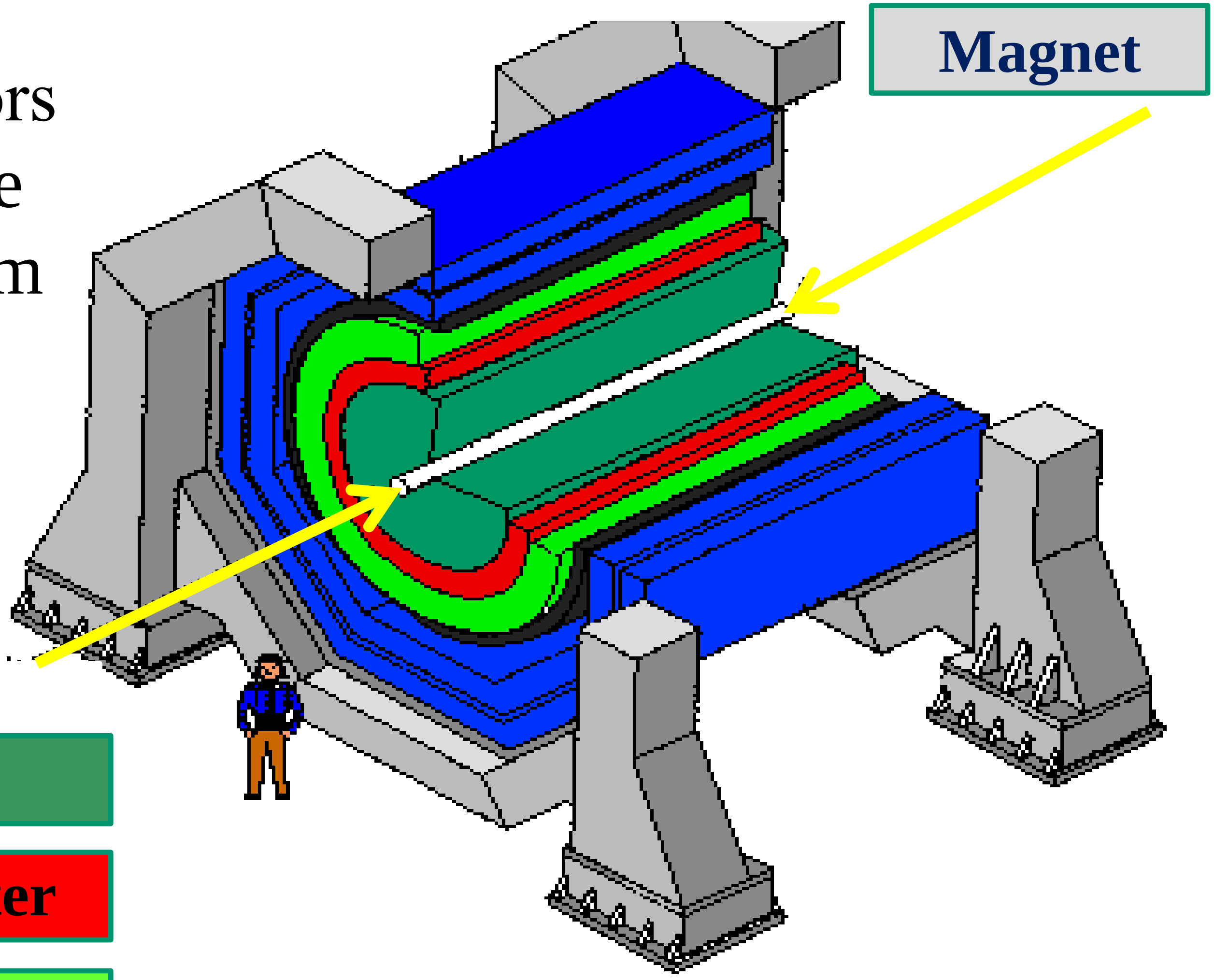
In particolare, il ruolo dei SiPM per applicazioni calorimetriche viene discusso ed e' illustrato con risultati del progetto FACTOR/TWICE (INFN Gr 5).

Aldo Penzo, INFN-Trieste

Padova, 14 Luglio 2011

Collider Detectors

“Collider detectors look similar since they must perform the same basic measurements.”



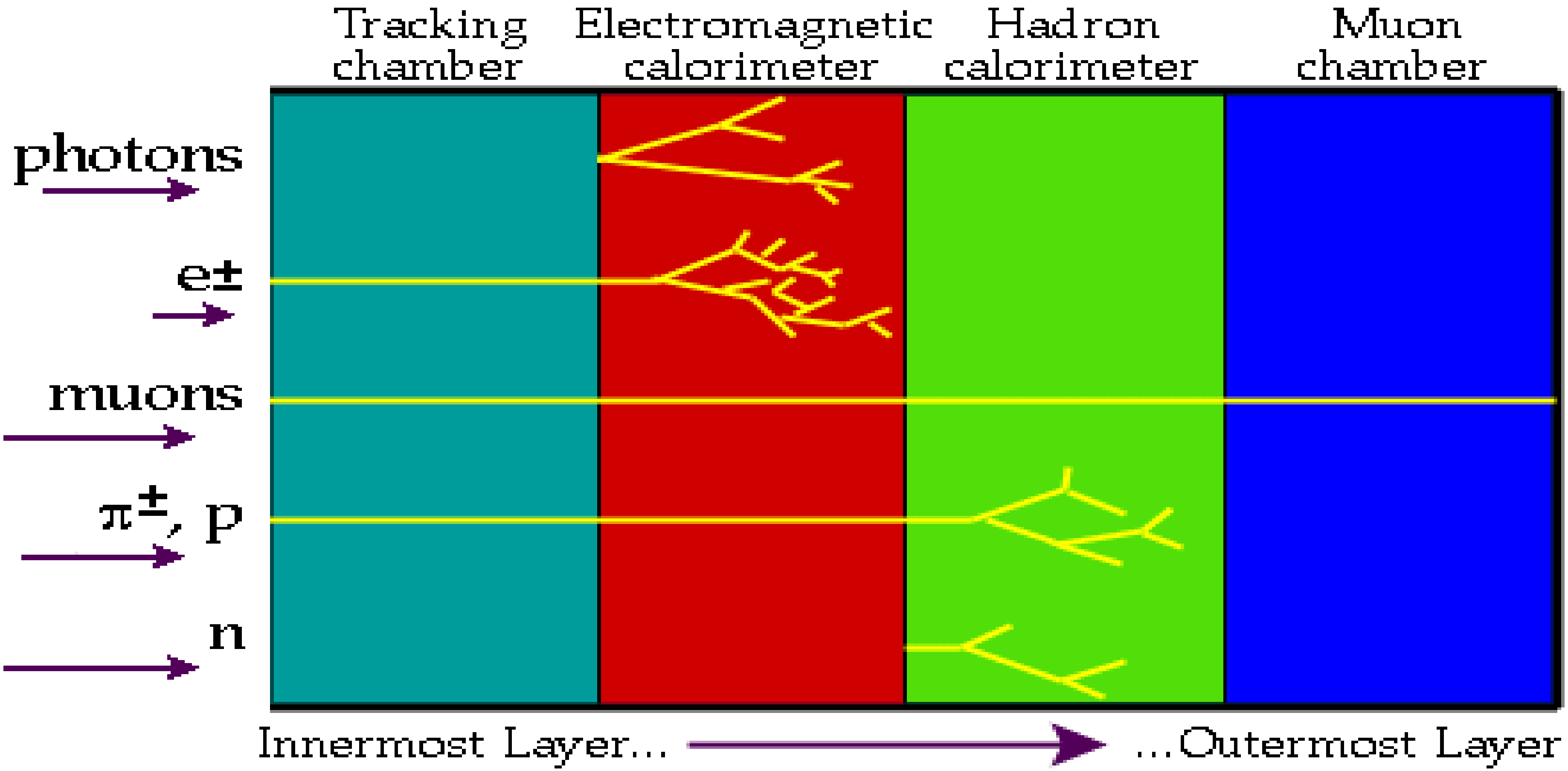
Tracking

EM Calorimeter

HAD Calorimeter

Muon

Main subdetectors



Various particles are measured by subdetectors and identified from their characteristic pattern .

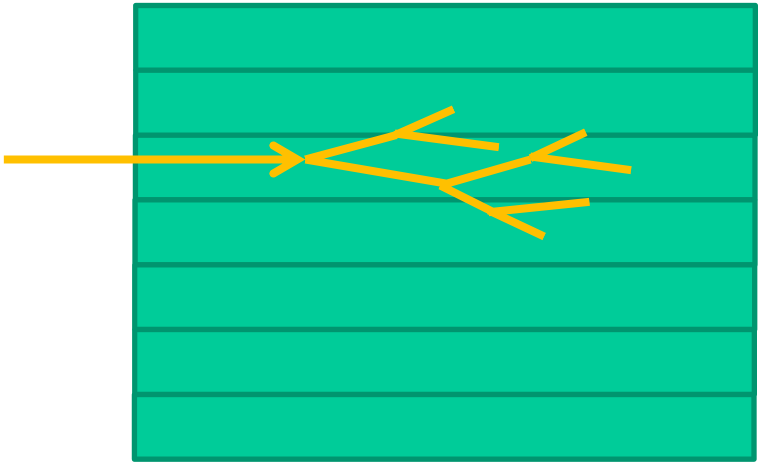
Calorimetria a LHC

- Una componente essenziale degli apparati installati sugli anelli di collisione di alta energia, ad esempio LHC, e' costituita da strumenti **calorimetrici**, in cui le particelle prodotte dalle collisioni dei fasci, depositano la loro energia, che viene misurata mediante **elementi attivi** contenuti nel calorimetro.
- In molti di tali esperimenti (ad esempio CDF al Tevatron di Fermilab, e nella maggioranza degli esperimenti a LHC) gli elementi attivi del calorimetro sono costituiti da materiale scintillante, il cui segnale luminoso viene raccolto da **fotorivelatori**, tradizionalmente tubi a vuoto.

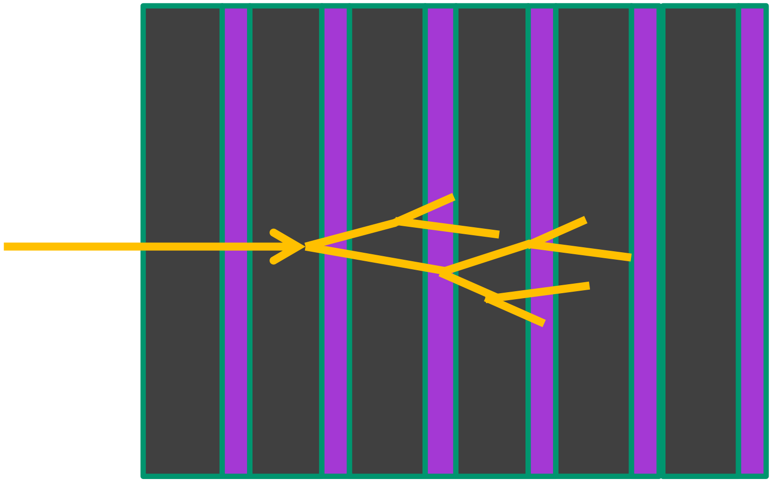
Calorimetry Issues

- Structure/Geometry
  - Sampling vs Homogeneous/Totally Active
  - Segmentation/Granularity
- Special Properties
  - Linearity, Dynamic Range, Energy Resolution
  - Compensation
- Functionality/Operation
  - Particle Flow Approach
  - Readout Options
  - Calibration

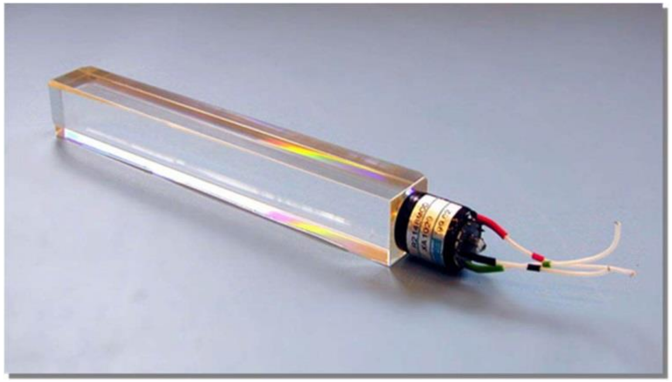
Homogeneous vs Sampling



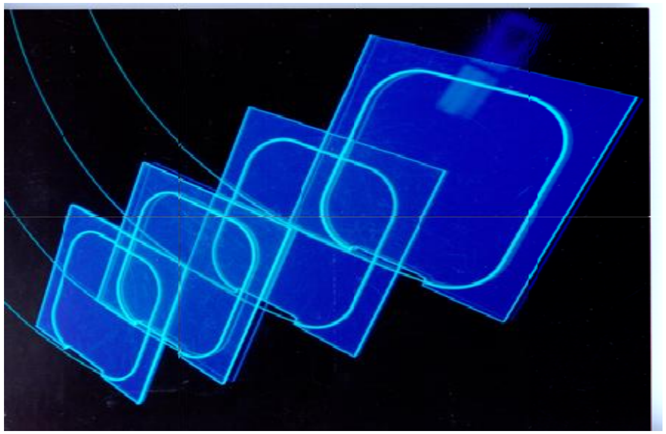
Absorber = active material



Absorber + active material

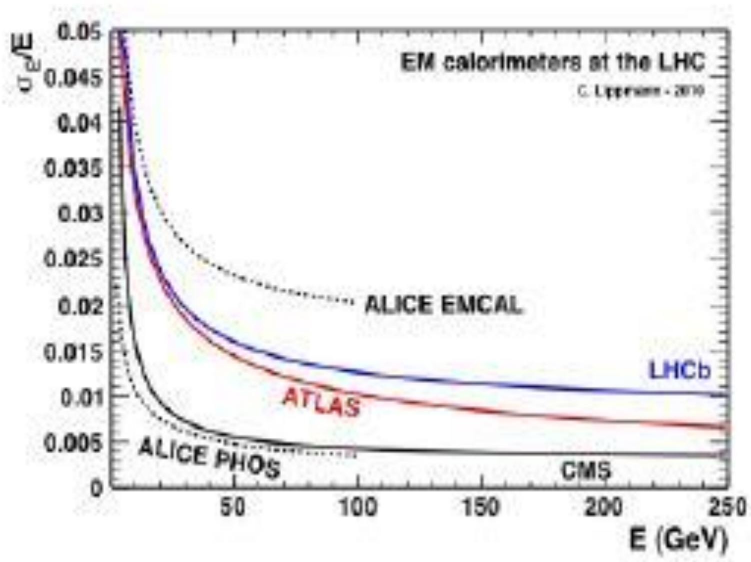


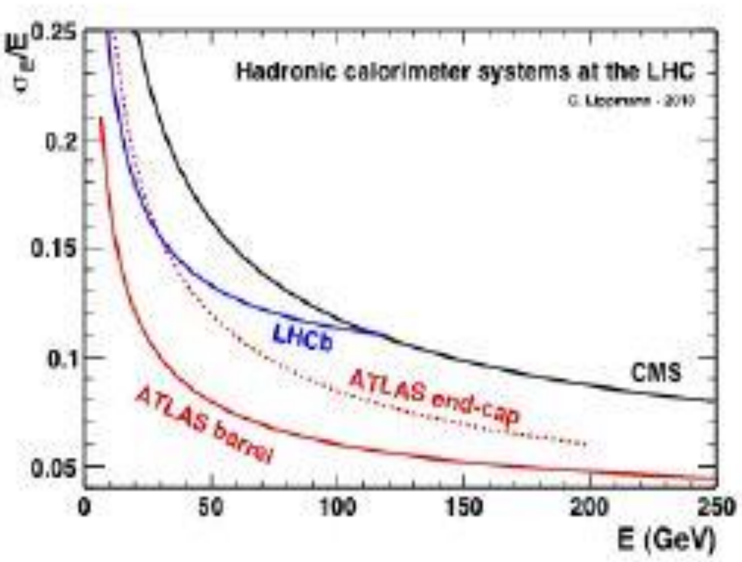
Heavy Crystals (PbWO)



Absorber plates +
Scintillator tiles

LHC Calorimeters' Survey





Stocastic term (fluctuations,etc)

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

Noise

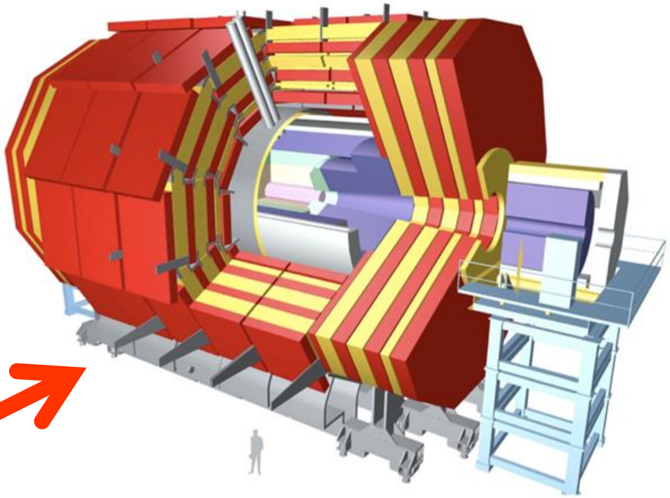
Constant term (calibration, non-linearity, etc)

Resolution Considerations

- For CMS **ECAL** the resolution measured in test-beam with electrons gives:
  - $a= 2.8\%$; $b =120 MeV$; $c= 0.3\%$
- ATLAS and CMS have sampling **hadronic** calorimeters with scintillator as active material. In both cases the dominant factor on resolution and linearity is non- compensation (e/h»1.4)
- CMS has $\sigma_E/E \approx 85\%/\sqrt{E}$ and ATLAS: $\sigma_E/E \approx 53\%/\sqrt{E}$
- This is not too bad for hadron colliders, where the interactions among constituents are not well defined kinematically; for lepton colliders, better resolutions would be paramount for precision measurements:

  $\sigma_E/E \approx 30\%/\sqrt{E}$ is considered the goal for LC.

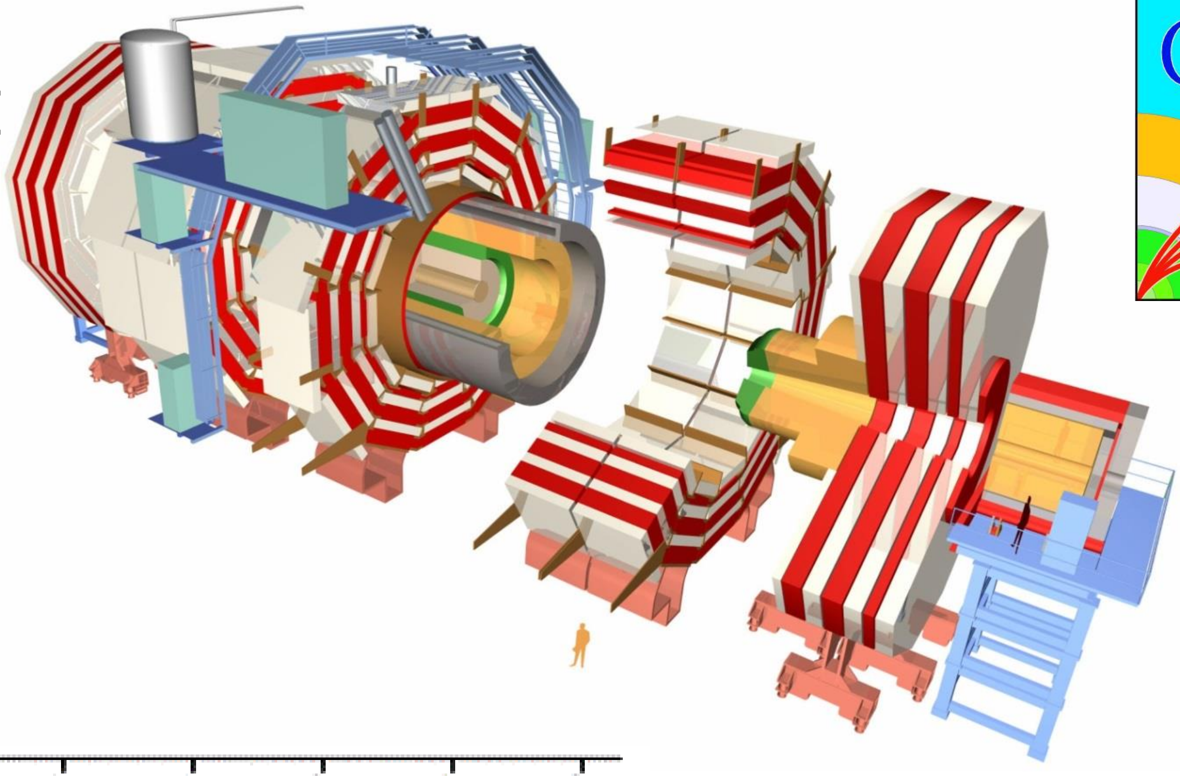
LHC Experiments

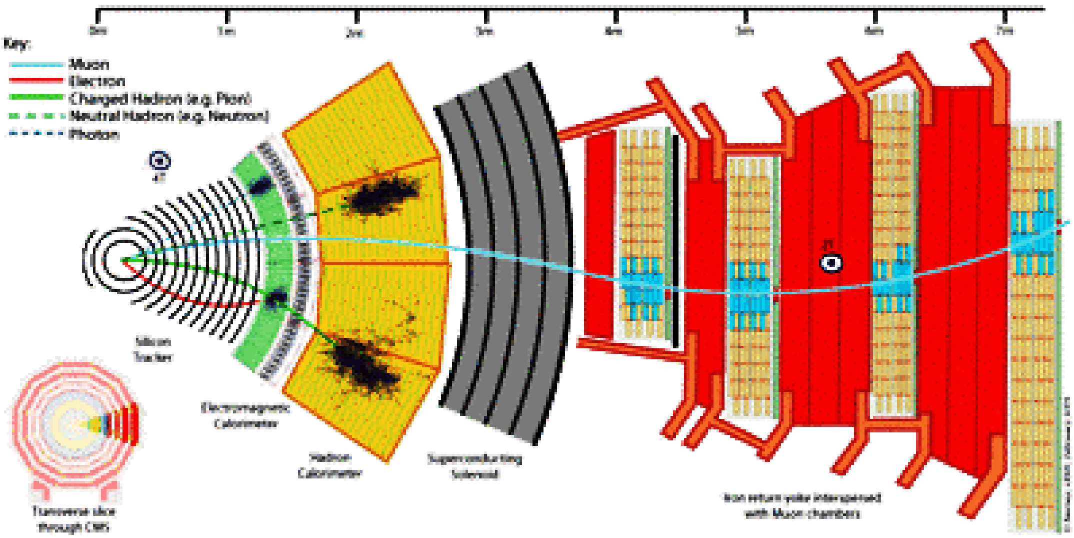


ATLAS **ALICE** **CMS**

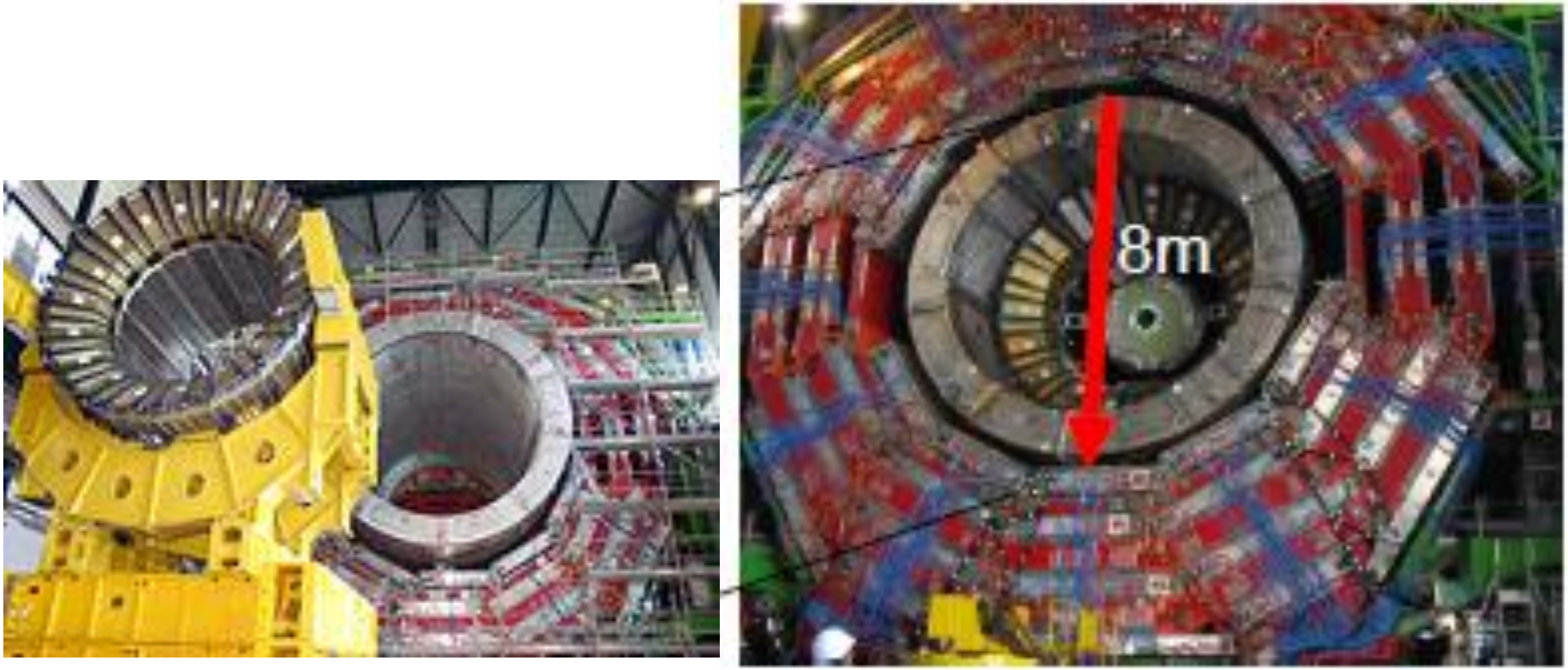
LHCb

Compact
Muon
Solenoid





Installing HCAL inside the Solenoid

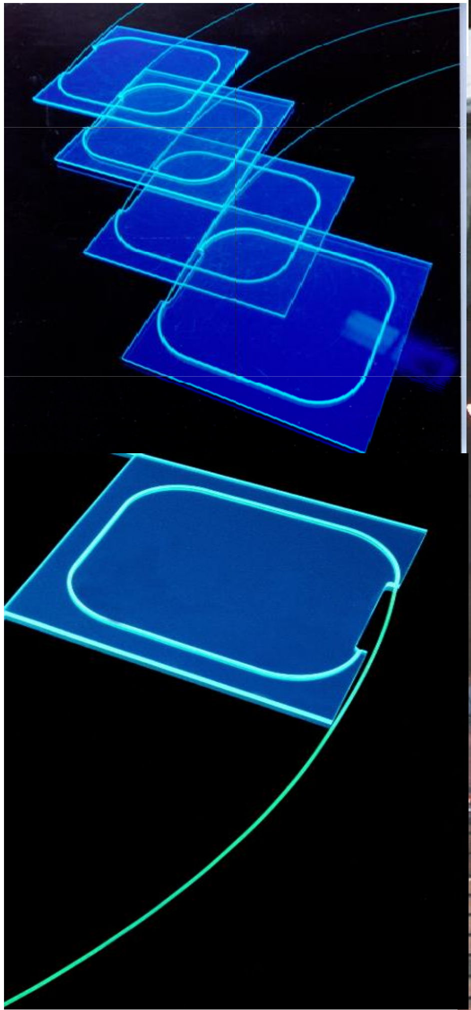


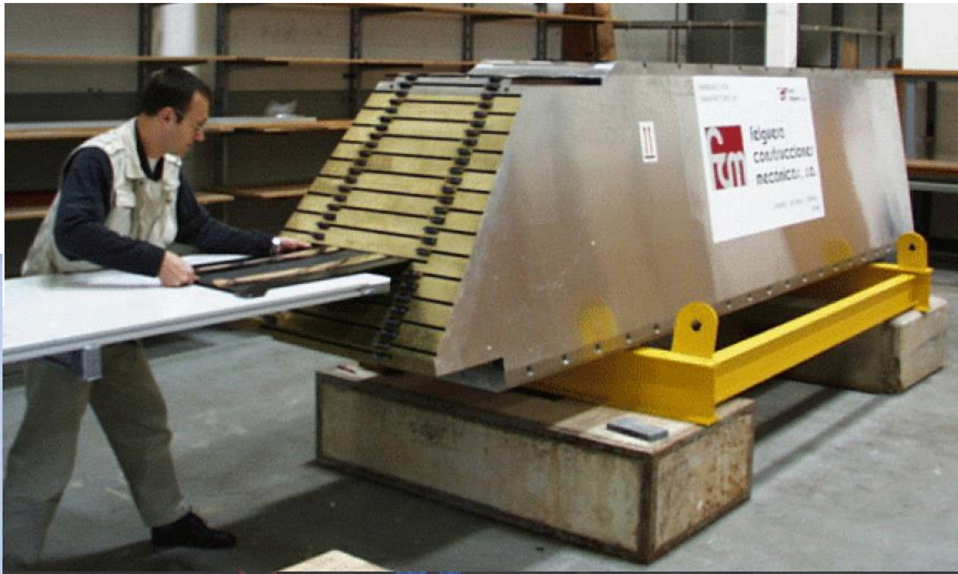
Each wedge weights 27 tonnes
In HB there are 36 wedges:
almost 1k tonnes total HB

HCAL Sampling Calorimeter

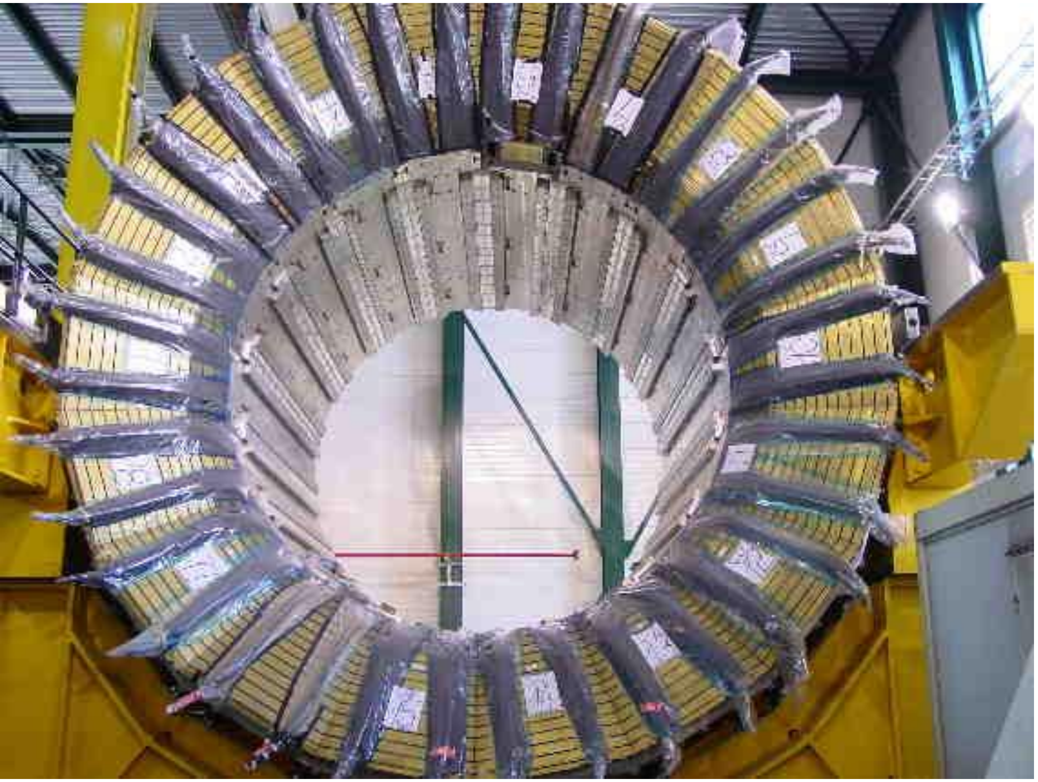
Brass Absorber plates
Scintillator tiles

WLS fibers placed in grooves in each scintillator tile.
About 5% of light is captured in the fiber.





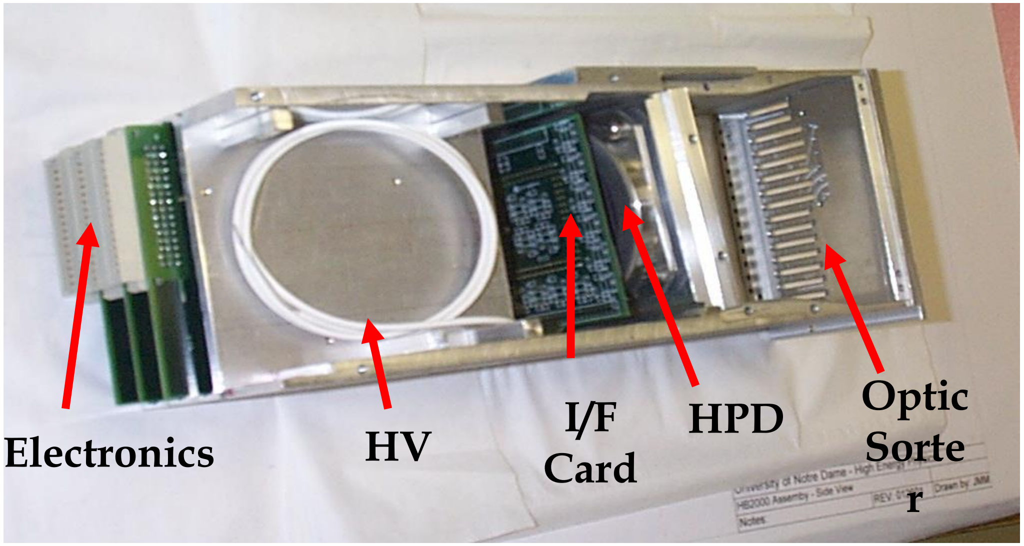
HCAL Readout



Optical manifold
Sorter/Coupler

HPD

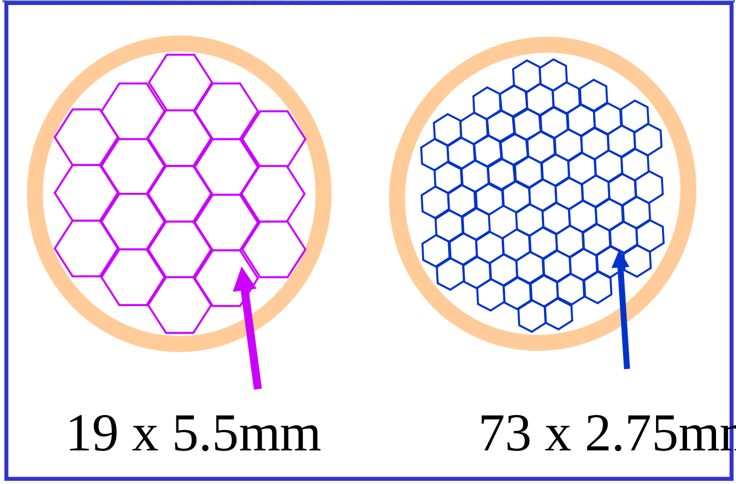
Fibers in front of HPD



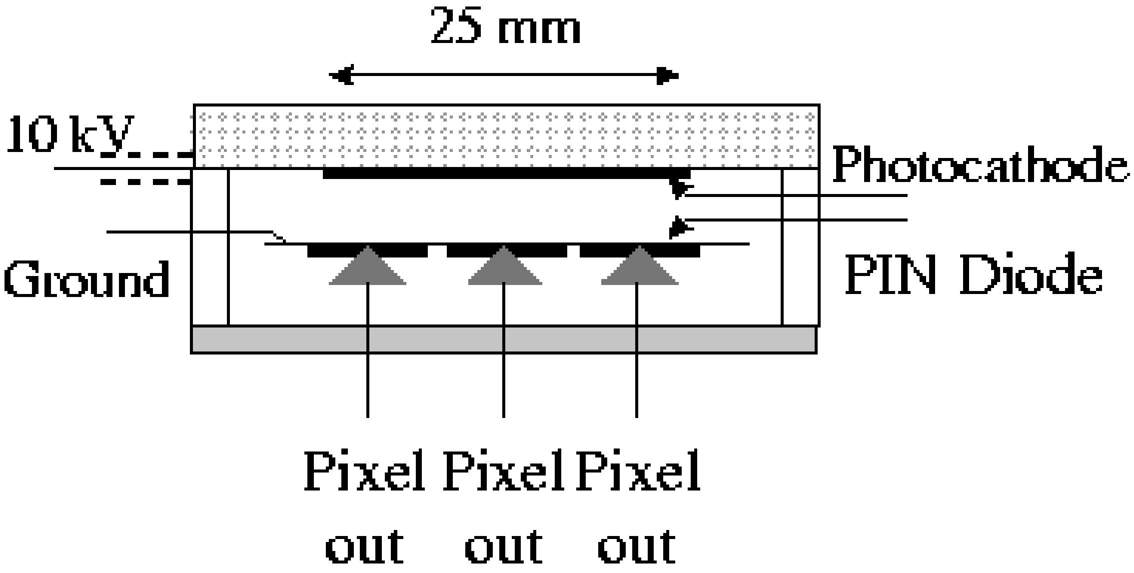
HPD

Hybrid PhotoDiode :

Fiberoptic front window
Standard Photocathode
Anode: pixelated diode

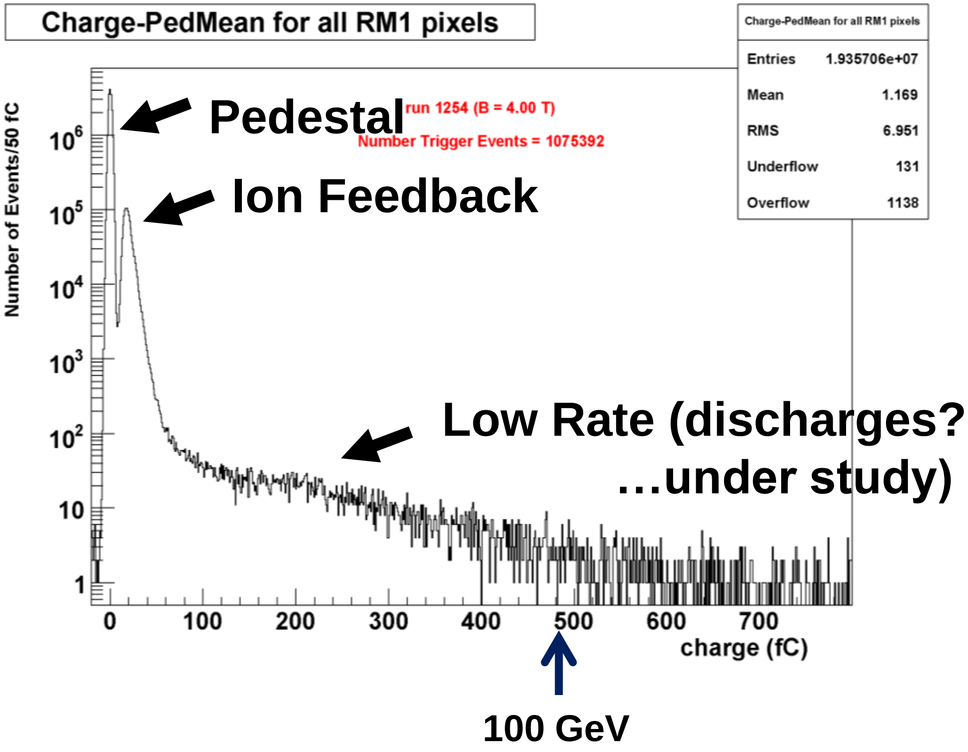

19 x 5.5mm
73 x 2.75mm

HCAL use 2 types of HPDs by DEP Holland) (19 or 73 channels/device) ~ 600 total



Known HPD Performance Issues

- HPD HV (-8kV) discharging though sidewalls
  - Uncontrolled discharging for 10% of HPD at 1T
- Signal Induced Ion Feedback
  - Probability of 2 x 10^{-4}/pe with 2-6 GeV pulses
  - Dark Current induced ion feedback

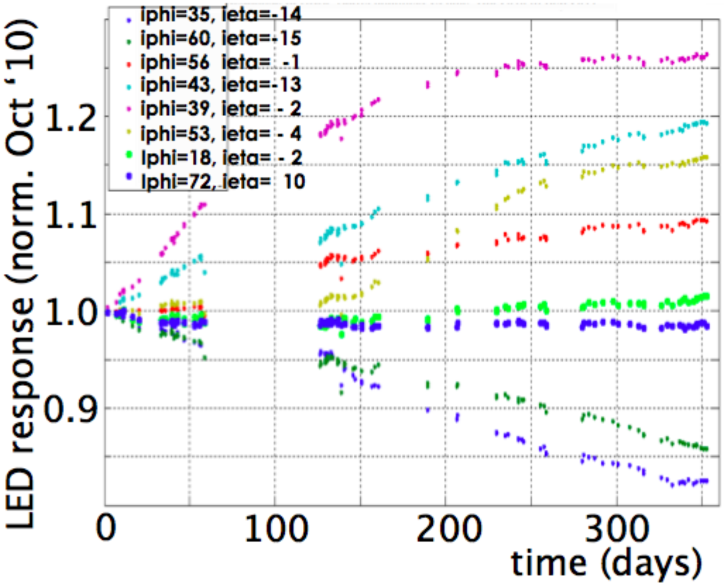


Pedestal

Ion Feedback

Low Rate (discharges?
…under study)

100 GeV



Gains drifted by up to 10-30% with time in 2011.

Hadronic vs EM response

Not all hadronic energy is “visible”:

→ Lost nuclear binding energy
→ neutrino escape
→ Slow neutrons, …

For instance in lead (Pb):
Nuclear break-up (invisible) energy: 42%
Ionization energy: 43%
Slow neutrons (E ~ 1 MeV): 12%
Low energy γ (E_γ ~ 1 MeV): 3%

Tot capita, tot sententiae…

Minimal basis of consensus:

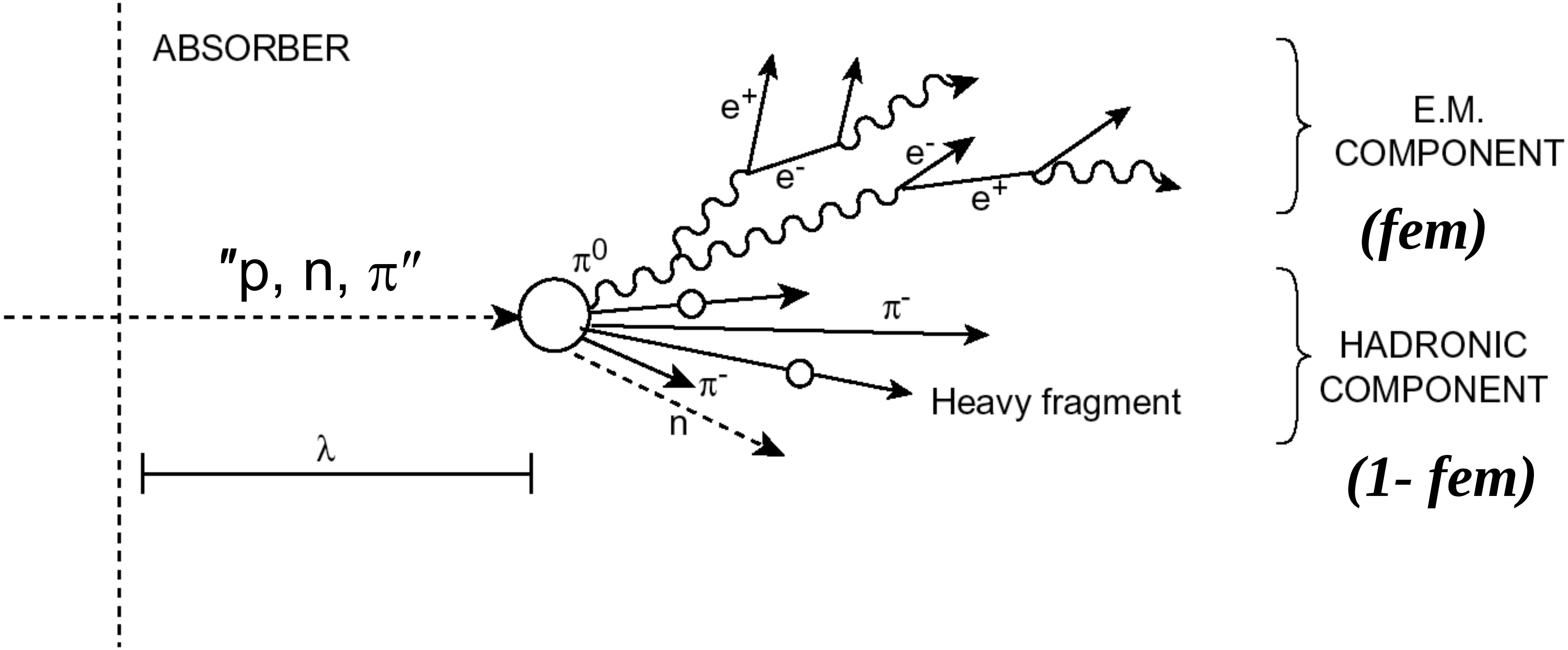
- ***EM calorimeters can be made "almost perfect"***
- ***HAD calorimeters are difficult to improve:***
  - ATLAS and CMS have sampling calorimeters with scintillator as active material. In both cases the dominant factor on resolution and linearity is non-compensation (e/h»1.4);
  - CMS has $\sigma_{E}/E \approx 85\%/\sqrt{E}$ and ATLAS $\sigma_{E}/E \approx 53\%/\sqrt{E}$
  - This is not too bad for hadron colliders, where the interactions among constituents are not well defined kinematically; for lepton colliders, better resolutions would be paramount for precision measurements:

  $\sigma_{E}/E \approx 30\%/\sqrt{E}$ is considered the goal for LC.

Compensation, the panacea?

- High precision hadron calorimeters should have equal response to electromagnetic and strongly interacting particles (compensation condition **e/h =1**) in showers generated by incoming hadrons, in order to achieve:
- linear response in energy to hadrons,
- gaussian energy distribution for mono-energetic hadrons,
- electron-to-pion ratio close to unity, constant with energy,
- relative energy resolution (dE/E), improving as sqrt(1/E).
- This is of prime relevance for the measurement of jets, involving various particles of different energies, with a substantial fraction of neutral pions..

Hadron Showers



Schematic of development of hadronic showers.

$$\pi = f_{em}\, e + (1- f_{em})\, h$$

- $e/\pi = e/h\,[1- f_{em}\,(1-e/h)]^{-1}$

Compensation methods
(mainly sampling calorimeters)

- **Intrinsic compensation:**
- Recover part of the “invisible energy”
- Decrease the electromagnetic contribution

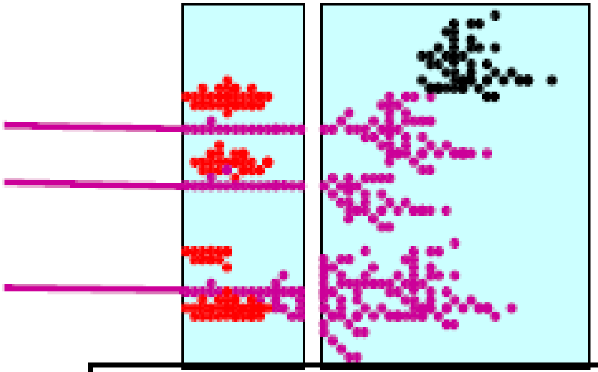
  (often using composite passive materials)
- **Off-line compensation:**
- Weighting methods
- Multiple shower measurements

  (with 2 or more active media, selective to EM,etc)

PFA: Particle Flow Approach

Typical fractions of jet energy:

- 60 % charged hadrons
- 30 % in photons
- 10 % in neutral hadrons



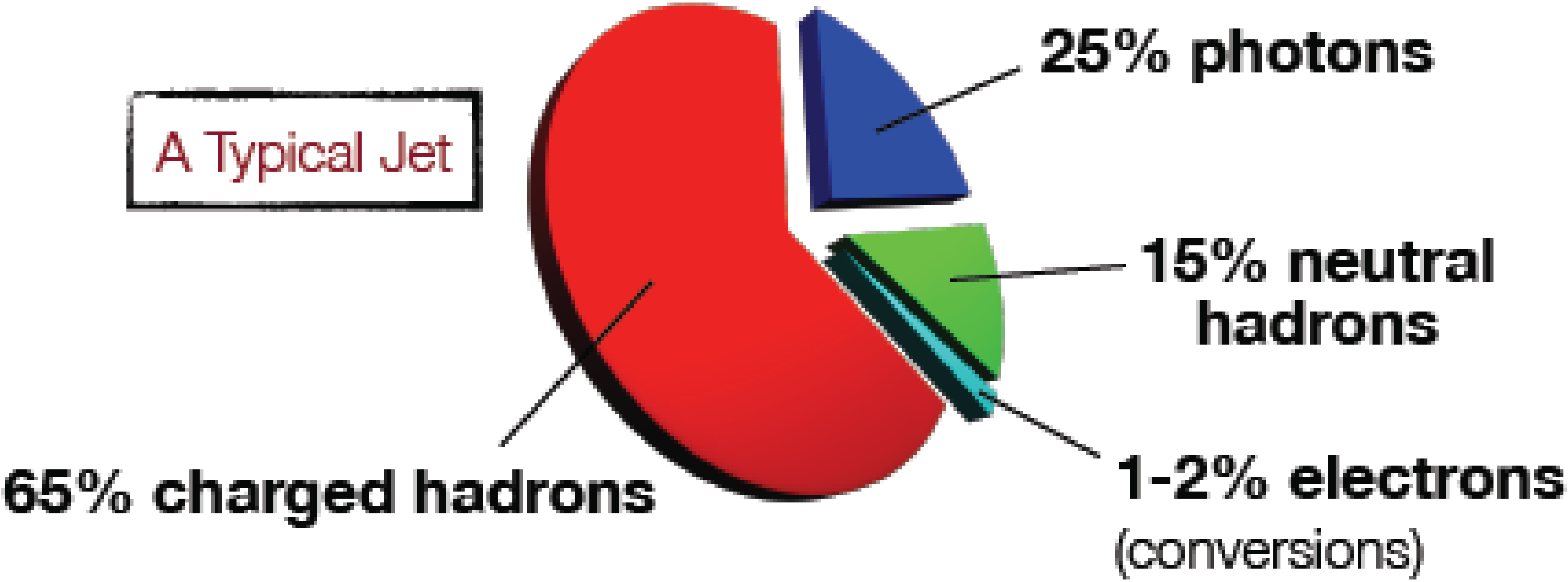
$$E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$$

Particle Flow Approach:

- **charged particles measured in tracker (almost perfect)**
- **Photons in ECAL**
- **Neutral hadrons (ONLY) in HCAL**
- **Only 10 % of jet energy from HCAL**

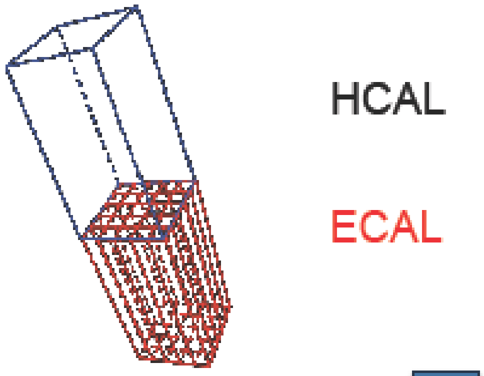
- **Requires high longitudinal and transverse granularity for unambiguous coupling of measured segments**

Jets



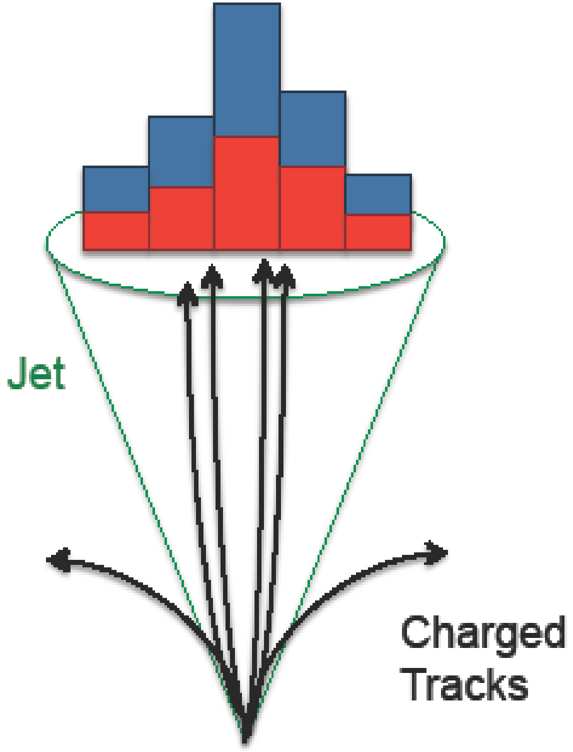
Subject to fluctuations…

Calorimeter Jets



- "Traditional" jet reconstruction
- Calorimeter Towers
  - 1 HCAL cell ~ 0.1 ($\Delta\phi$ x $\Delta\eta$)
  - 25 ECAL crystals ~ 0.01 ($\Delta\phi$ x $\Delta\eta$)
- Does not make use of ECAL granularity
- Jet resolution driven by HCAL:
  - HCAL resolution ~ $100\%/\sqrt{E}$
  - non-compensating → non-linear response
- Low p_T charged hadrons bent outside jet

Purely calorimetric jet reconstruction does not take advantage of the full versatility of CMS



Particle Flow Jets

Particle flow reconstructs all stable particle in the event: $h^{+/-}$, γ, h^0, e, μ with thorough combination of all sub-detectors in CMS

- On average jets are:

~ 65% charged hadrons, ~ 25% photons, ~ 10 % neutral hadrons

- Using the silicon tracker (vs. HCAL) to measure charged hadrons

Particle Flow (continue)

Reconstruct each particle in a jet with Tracker+ECAL+HCAL
– Charged particles by Tracker: ~64% of jet energy
– Photons with ECAL: ~25% of jet energy
– Neutral hadrons with HCAL: ~11% of jet energy

Particle flow algorithm (PFA)

$$\mathrm{Ejet}=\Sigma|P|\mathrm{ch}+\Sigma \mathrm{Eph}+\Sigma \mathrm{En.h}$$

$$\sigma^2\mathrm{jet}=\sigma^2\mathrm{ch.}+\sigma^2\mathrm{ph.}+\sigma^2\mathrm{n.h.}+\sigma^2\mathrm{confusion}$$

•Particle flow (Energy flow) algorithm was used already at LEP, but LEP detectors were not optimized for PFA.
σconfusion is large - must be minimized:
– Track-cluster matching
– Separation of overlapping clusters

– Measuring charged particles in tracker removes dominant part of hadronic energy fluctuations
– Requires high longitudinal and transverse granularity

As the contribution of neutral hadrons is small, the HCAL energy resolution may be moderate for single hadrons.

Still need good hadron energy resolution!

Options for Calorimetry with SiPM

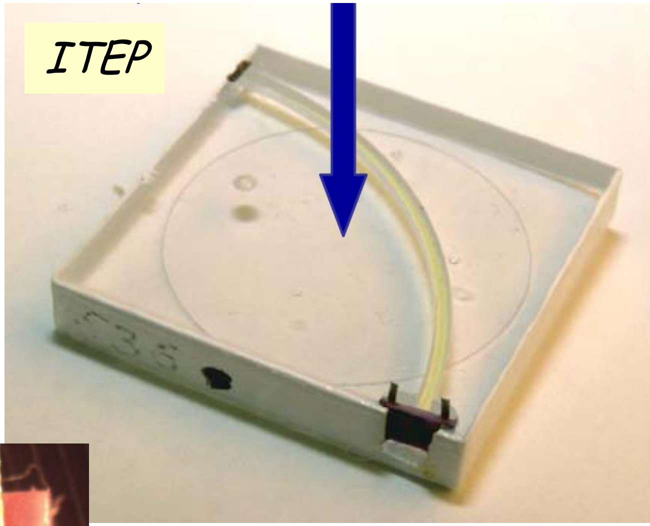
- **SiPM** perfectly match high granularity sampling calorimeters (small scintillator tiles+WLS fibers), avdocated by **PFA** & epitomized by **CALICE**
- Limitations due to small size and low dynamic range (number of pixels) are not critical for this application

- Other options of calorimetry:
  - sampling (spaghetti, shashlik, dual R/O) or
  - total absorption (heavy glass and/or crystals)

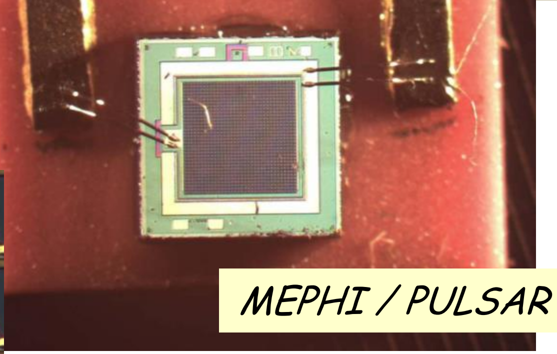
need larger dimensions and higher dynamic range

Calice Mini-Tiles with SiPM

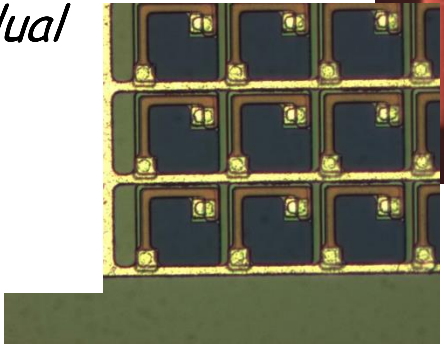
- SiPMs from MEPHI / PULSAR
  - Developed in collaboration with DESY
  - Gain 10^6, bias ~ 50 V, size 1 mm2
  - C ~ 50 fF, R = 0.4…20 MΩ
  - Overvoltage ~ 3V
  - Temp. sensitivity: gain 2%/K, signal 5%/K



3x3 x 0.5 cm scintillator tile with WLS fibre (1mm)



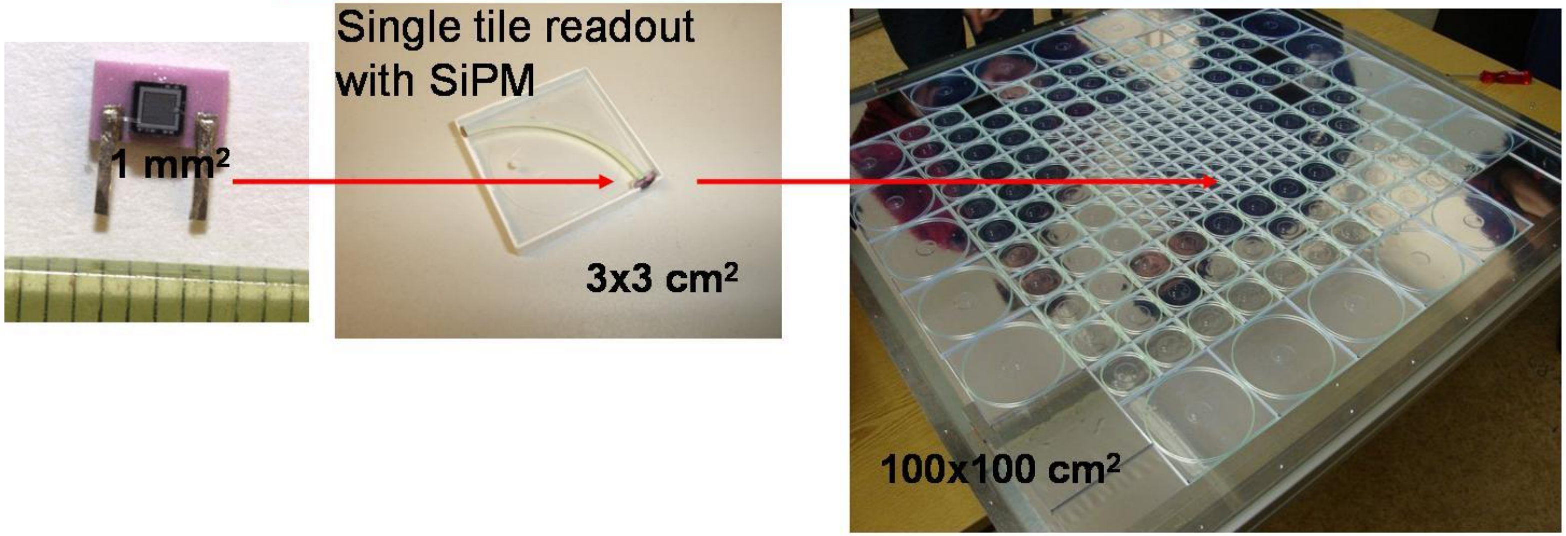
1156 pixels with individual quenching resistor on common substrate

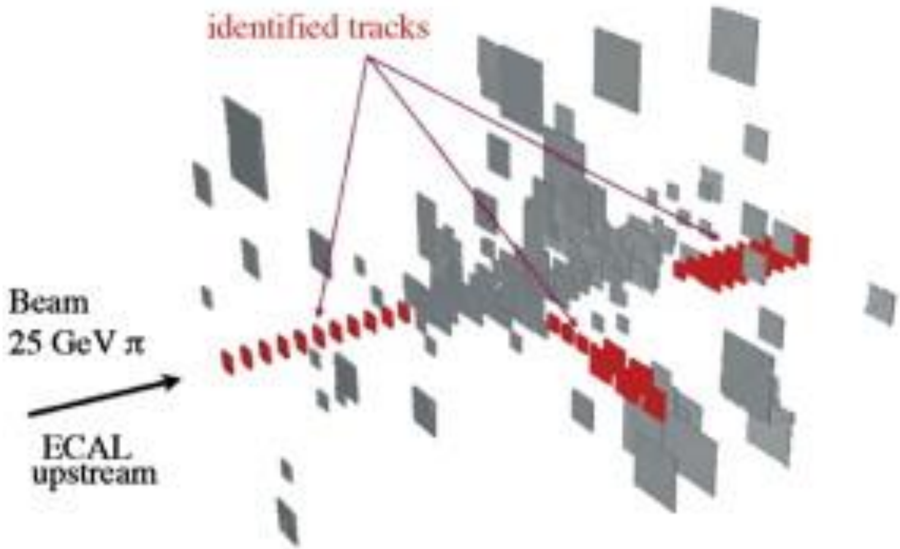


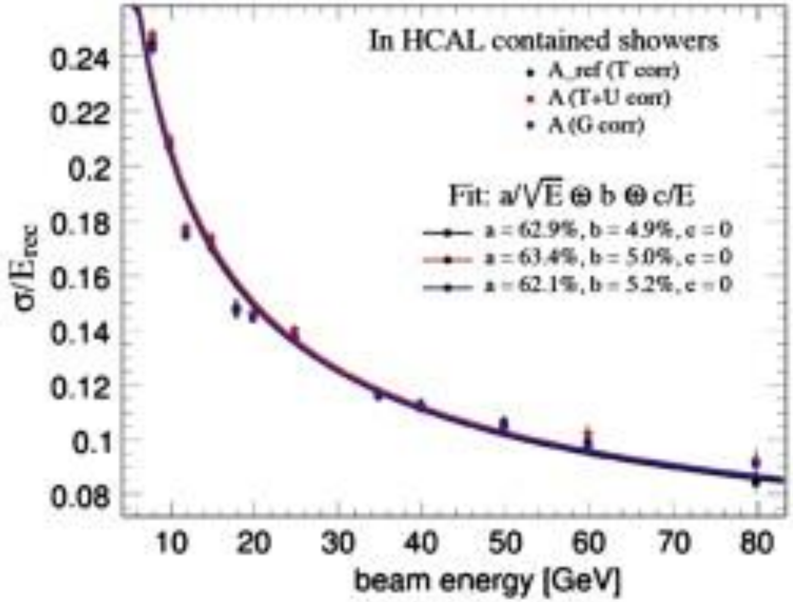
New era for scintillator-based detectors:
High granularity** at relatively **low cost

CALICE

A crucial technology improvement to calorimetry


Single tile readout with SiPM





Tendenza generale

- Fotorivelatori al silicio stanno prendendo il posto dei tubi fotomoltiplicatori a vuoto in molte applicazioni,
- In particolare nel campo della fisica sperimentale delle particelle, ad esempio negli esperimenti a LHC
- Nei programmi di incremento di tali rivelatori ai massimi livelli di efficienza per le prossime fasi di sperimentazione a LHC (con importanti aumenti di energia e luminosita’) e’ previsto in molti casi di sostituire i fotorivelatori a vuoto con SiPM.
- Cio’ ha portato ad un intenso programma di ricerca e sviluppo in collaborazione fra ricercatori e produttori di SiPM al fine di giungere a standard adeguati alle esigenze sperimentali ed alle condizioni particolari di impiego.
- **E’ questo il caso del calorimetro adronico di CMS, che verra’ illustrato in dettaglio.**

Solid State Photon Detectors

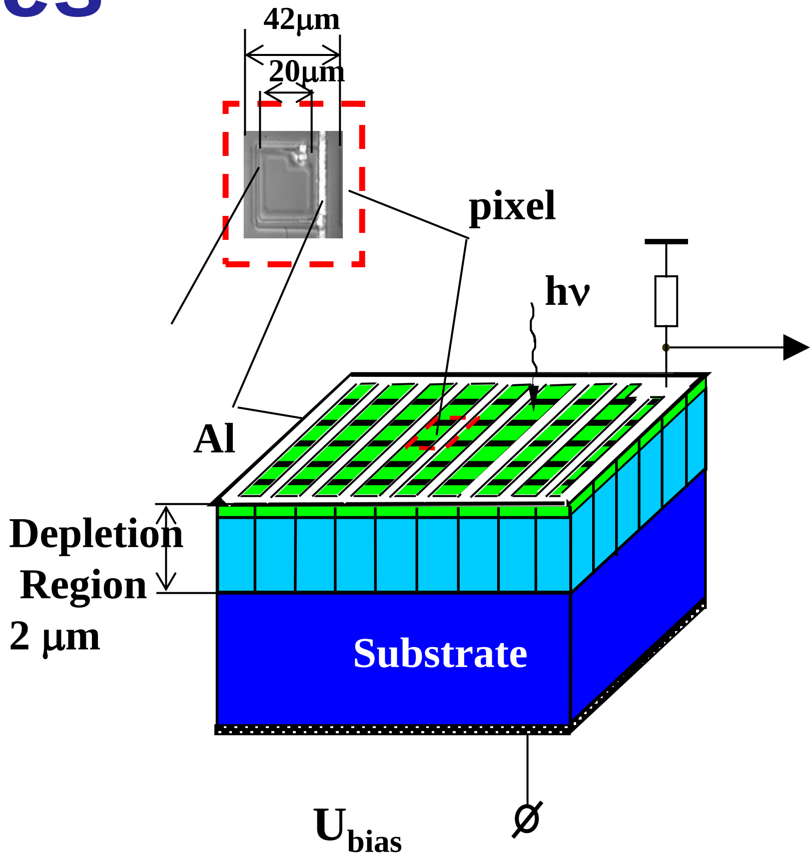
SPAD	Single Photon Avalanche Diode (single or arrays)
SiPM	Silicon PhotoMultiplier
MRS	Metallic Resistive Semiconductor
MPGM APD	Multipixel Geiger-mode Avalanche PhotoDiode
AMPD	Avalanche Micro-pixel PhotoDiode
SSPM	Solid State PhotoMultiplier
GAPD	Geiger-mode Avalanche PhotoDiode
GMPD	Geiger-Mode PhotoDiode
DPPD	Digital Pixel PhotoDiode
MCPC	MicroCell Photon Counter
MAD	Multicell Avalanche Diode

- …
- **Different acronyms for quasi-identical components**
  - **Variants historical, technological, geographical**

Basic Properties

Multipixel Geiger Mode APD

- Gain 10^6
- Bias U~50 V
- Active area 1-10 mm^2
- 1156 pixels, 20μm × 20μm
- Efficiency 10-15%
- Insensitive to B field
- Each pixel has quenching resistor (few MΩ)
- Recovery time < 100 ns



SiPM R&D

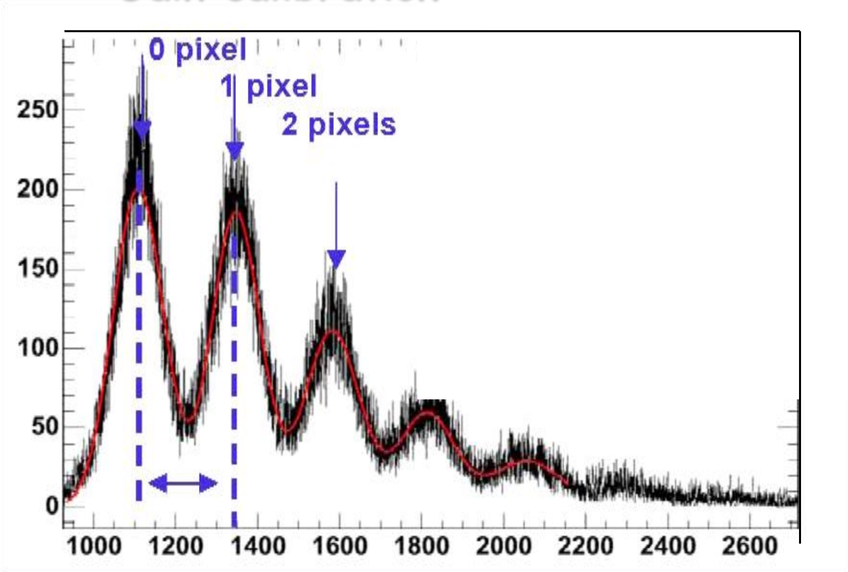
- **SiPMs Sources**:
  - **CPTA** Moscow
  - **MEPhi/Pulsar**, Moscow
  - **Dubna/Micron** (MSR, Metal Resistive Layer)
  - **Hamamatsu**, Japan (“MPPC”)
  - **SensL**, Ireland
  - **FBK-IRST**, Trento
  - **SiLite**, Tennessee
  - **ForimTech**, Geneva
  - **PHOTONIQUE,** Geneva
  - **MarketTech**
  - **MPI,** Germany
  - **ZEKOTEK,** Singapore
  - **ST,** Italy
  - **NDL,** Beijin
  - **KETEK,** Germany

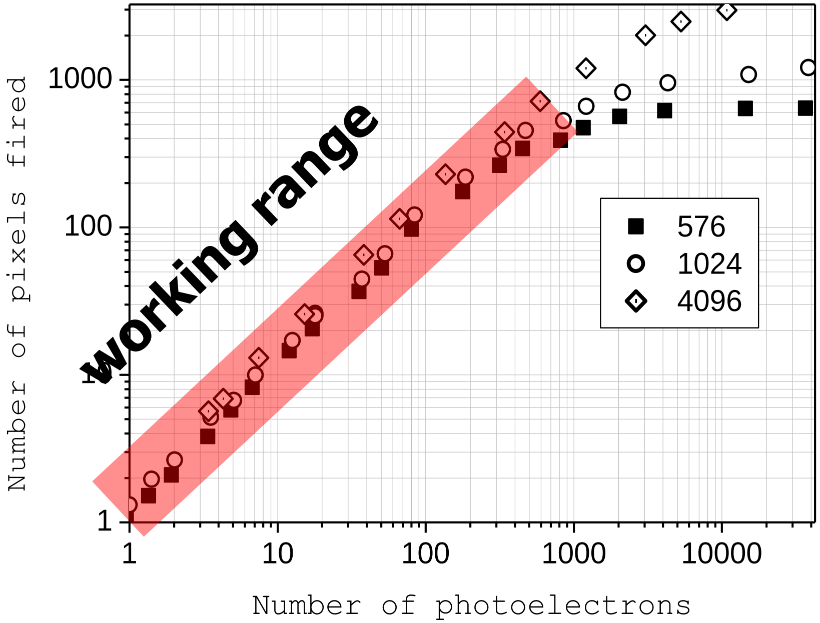
Active Groups/Collaborations

- CALICE (ILC): > 5000 SiPM tested
- CMS (LHC): HCAL Upgrade
- FNAL: T2K, SiDET (ILC)
- In Italy:
  - P-ILC: Frascati, Roma1, Como
  - DASIPM2, Del Guerra, Battiston et al., (Pisa, Bari, Bologna, Perugia, Trento) - medical applications (high resolution PET), space physics, HEP
  - FACTOR (Trieste, Udine, Roma, Messina) calorimetry
  - TWICE (FACTOR+Napoli+Salento)
  - Many more with time…

Response and Dynamic Range

Gain calibration

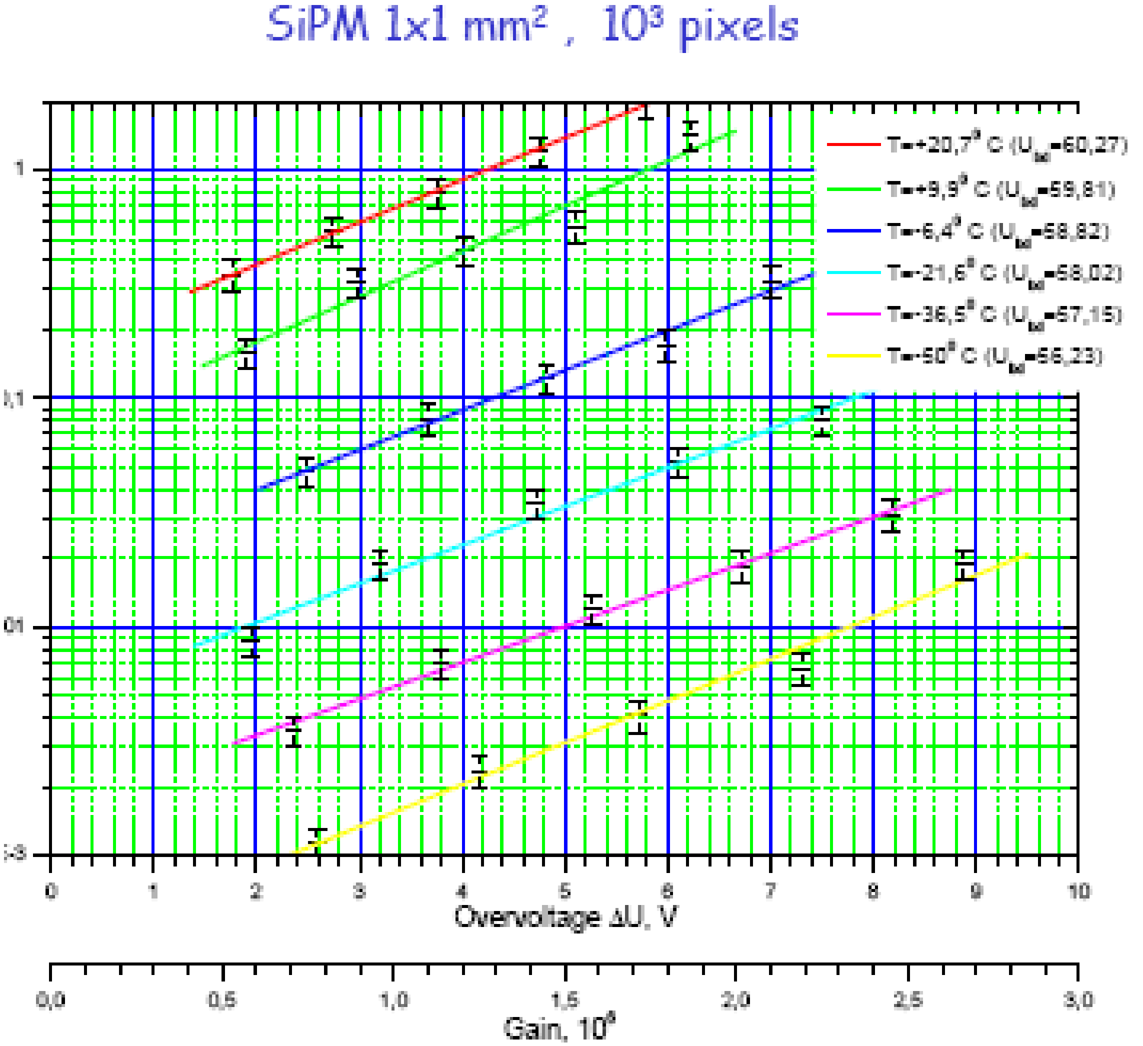




- SiPM is “photon counter”, but for too many photons saturation effects appear

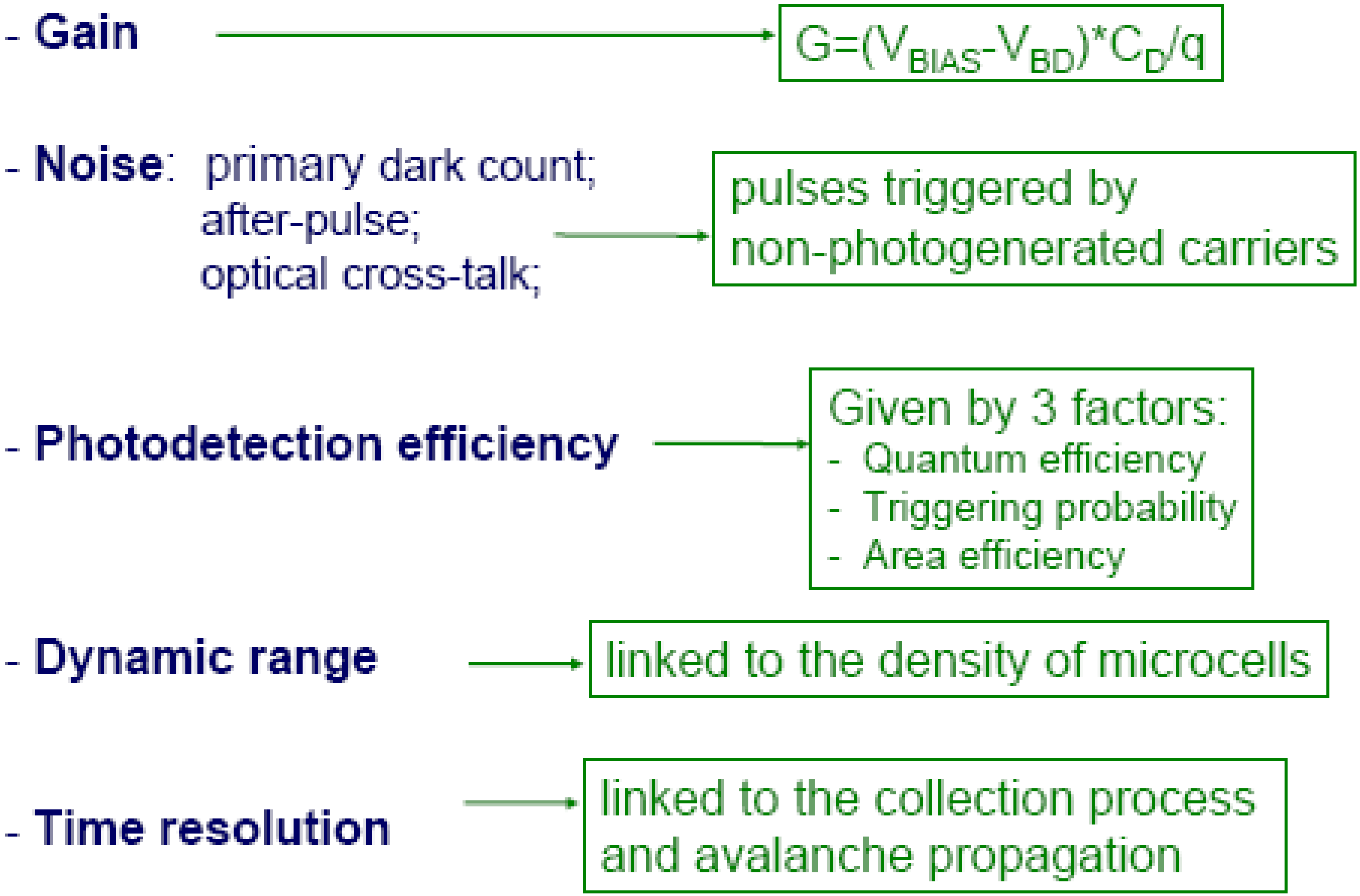
Dark Rate

- Thermally generated currents: Dark Rate
- - Increases with gain (tunneling)
- - problem for large area devices (~50 MHz fro 5x5 mm2 at room temp.)
- - cooling helps (but beware of afterpulsing)



B.Dolgoshein,'Large area SiPM's...'

Parameters of SiPM



- **Gain** → $G=(V_{BIAS}-V_{BD})*C_D/q$

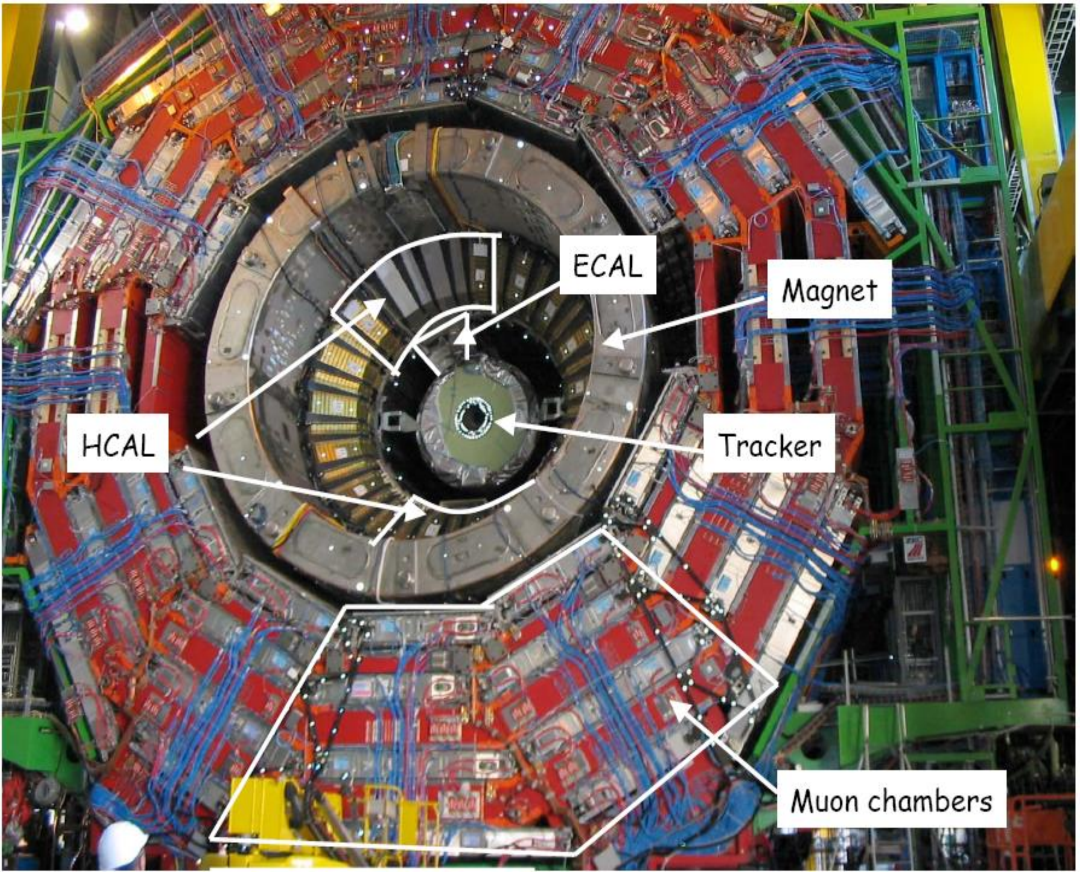
- **Noise**: primary dark count; after-pulse; optical cross-talk; → pulses triggered by non-photogenerated carriers

- **Photodetection efficiency** → Given by 3 factors:
  - Quantum efficiency
  - Triggering probability
  - Area efficiency

- **Dynamic range** → linked to the density of microcells

- **Time resolution** → linked to the collection process and avalanche propagation

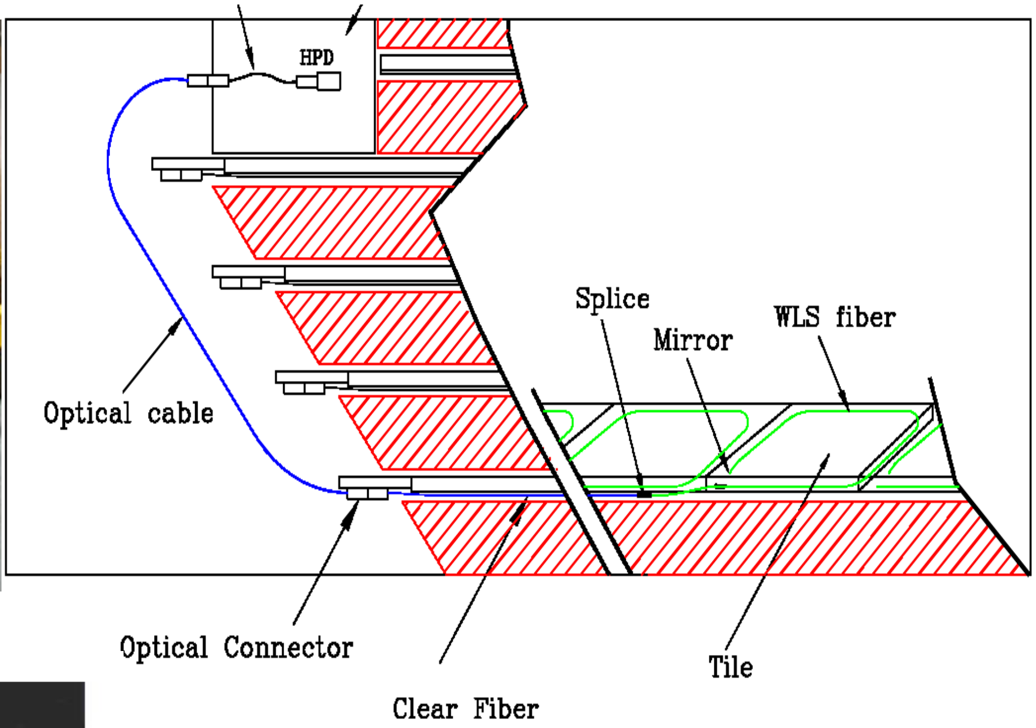
SiPM for CMS HCAL upgrade

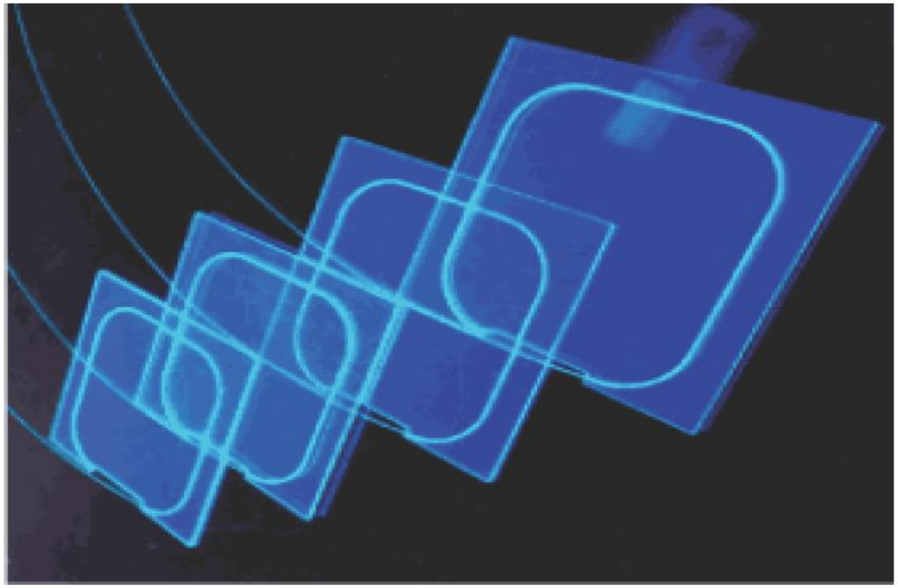


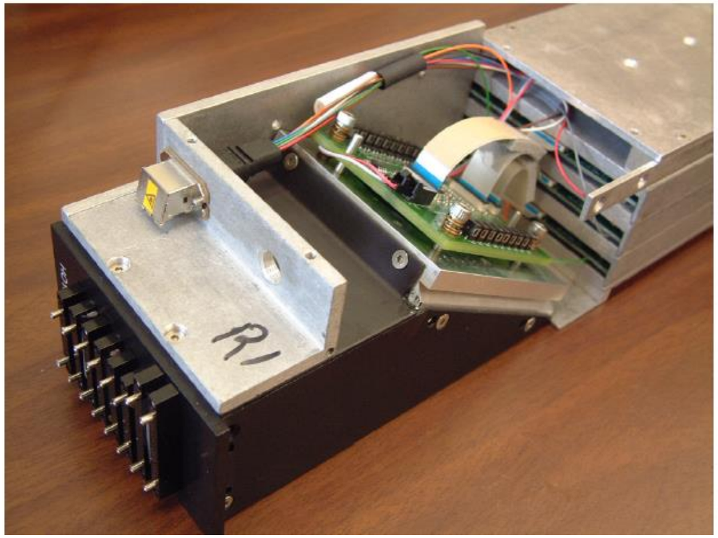
44,064 Barrel fibers 0.94mm diam (~42 cm^2 total area)

- Develop SiPM devices that meet CMS HCAL specs
- Upgrade version of the digitization electronics (QIE10) first version of new design submitted for fabrication
- Upgrade digital link chips
- Upgrade voltage regulators
- replace Low Voltage power supplies
- 6-7 MUSD costs
- (2MUSD for SiPM)

HCAL Wedges, Tiles and Readout

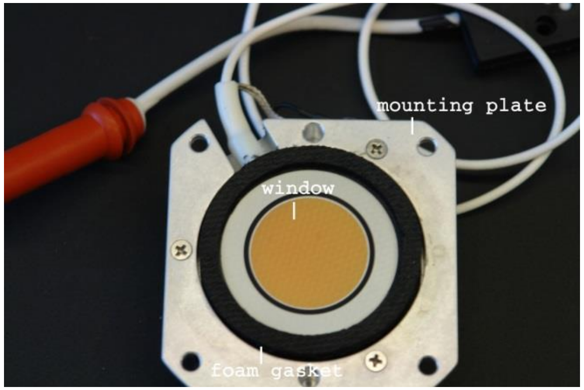


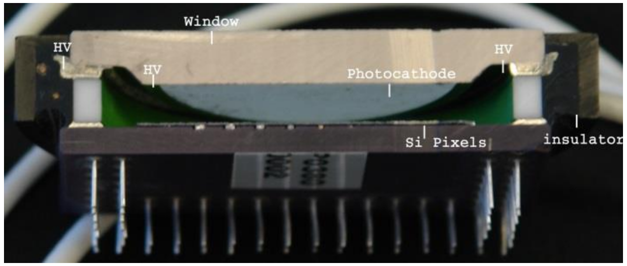




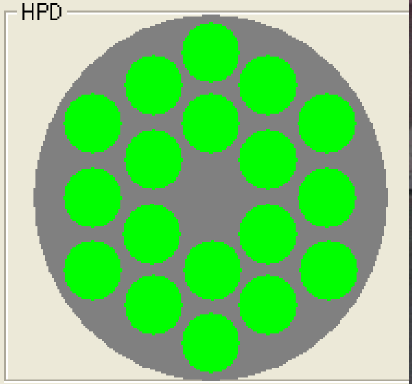
CMS HCAL Barrel/Endcap HPD Photodetectors and Optical Mapping

Hybrid PhotoDiode (HPD)
Gain ~x2000



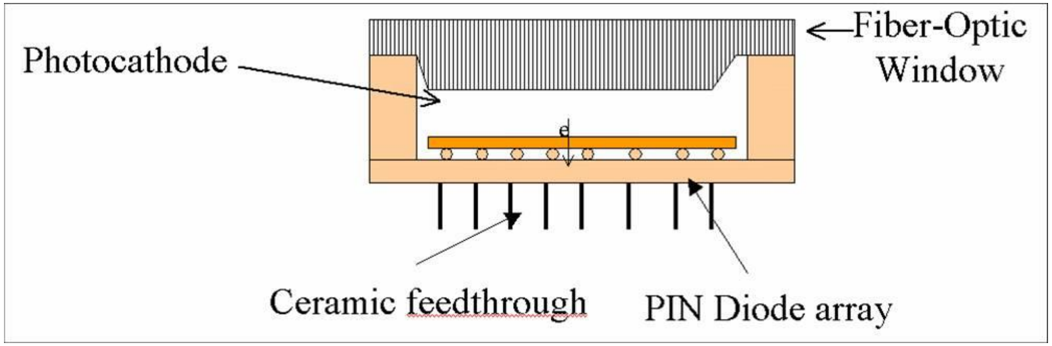


19 pixel diode



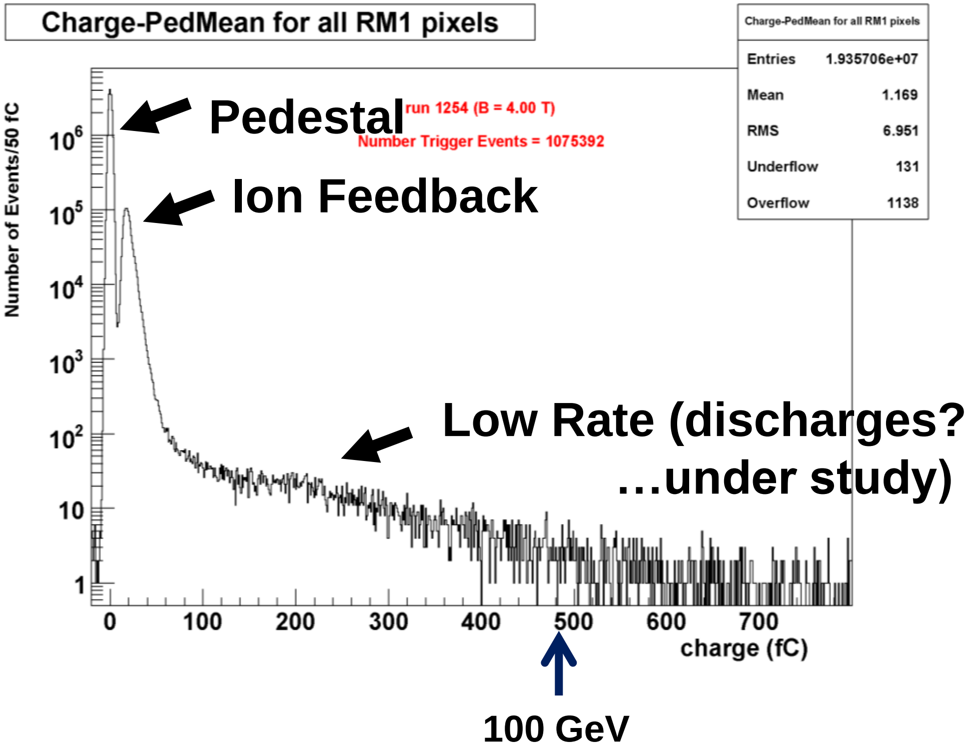
5 fibers/pixel

Barrel Optical Decoding Unit



Known HPD Performance Issues

- HPD HV (-8kV) discharging though sidewalls
  - Uncontrolled discharging for 10% of HPD at 1T
- Signal Induced Ion Feedback
  - Probability of 2 x 10^{-4}/pe with 2-6 GeV pulses
  - Dark Current induced ion feedback

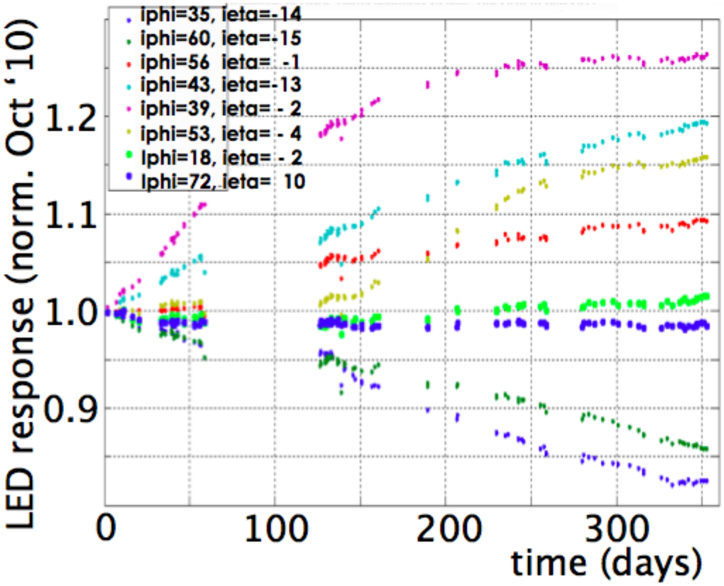


Pedestal

Ion Feedback

Low Rate (discharges?
…under study)

100 GeV

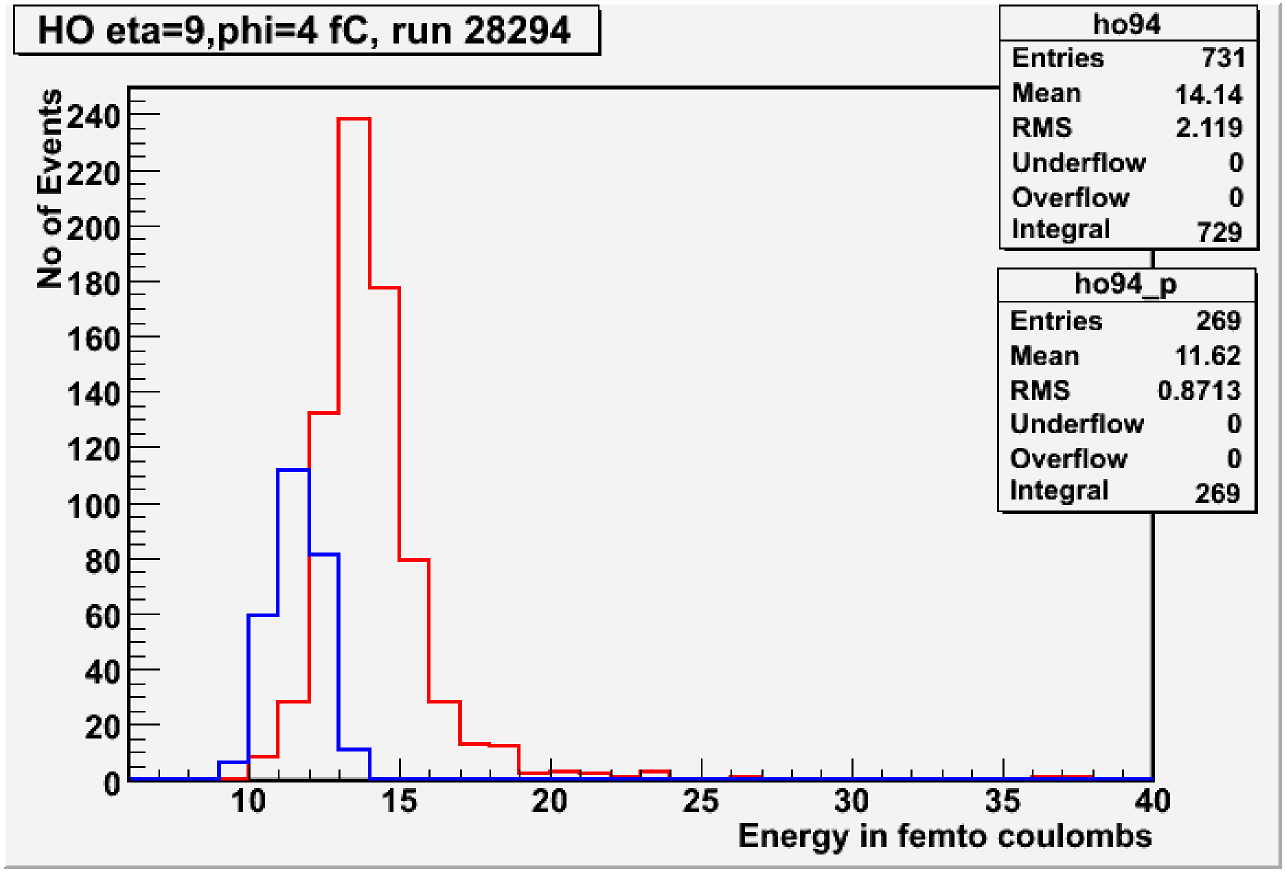


Gains drifted by up to 10-30% with time in 2011.

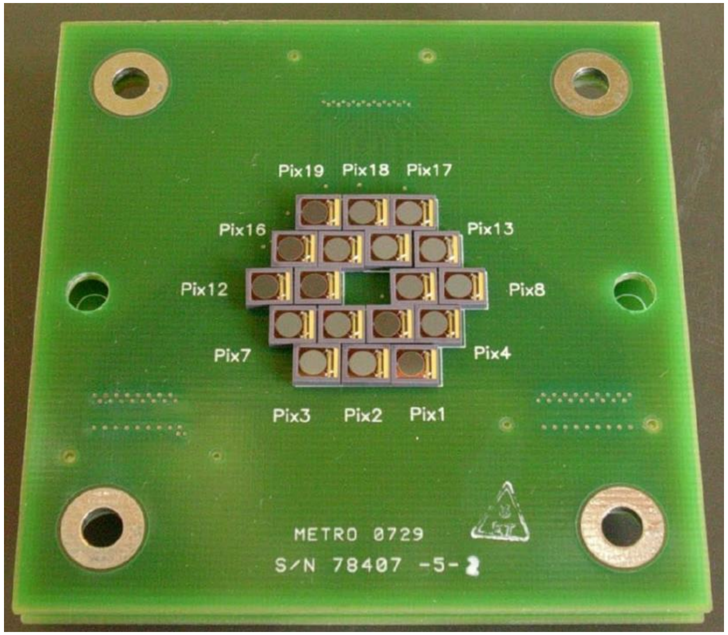
Motivations for HB/HE photodetector upgrade

- SiPM have ***better quantum efficiency, higher gain, and better immunity to magnetic fields*** than HPDs.
- Since SiPM operate at relatively ***low voltages***, they do not produce large pulses from high voltage breakdown that mimic energetic showers like HPDs do.
- These features of the SiPM together with their low cost and compact size compared to HPDs enable several major changes to the HCAL.
  - Implementation of ***depth segmentation*** which has advantages in coping with higher luminosities and compensating for radiation damage to the scintillators.
  - Use of ***timing*** to clean up backgrounds; SiPM have large gain and better signal-to-noise of the HPD.

HPD Muon signal at 8 kV



Replacing HPD with SiPM

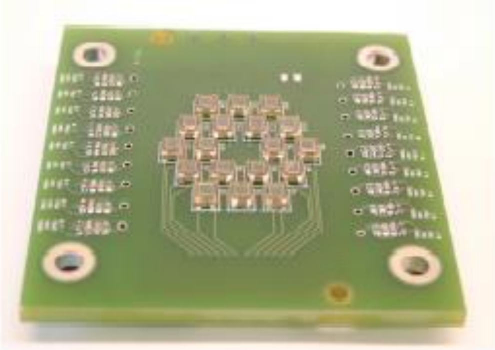


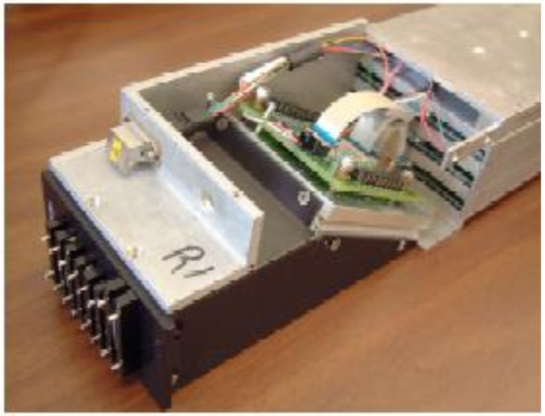
IRST

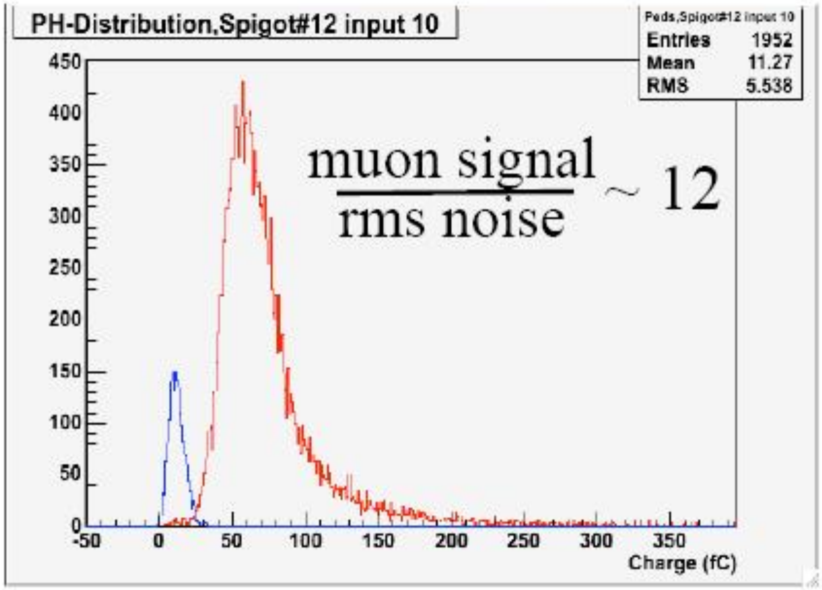
Custom 2.8 mm diameter
(2500 pixels)
Kyocera package
Packaged at CERN

First tests with SiPM

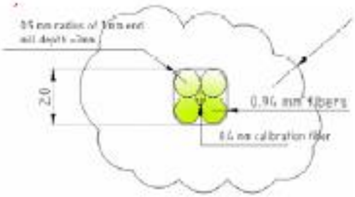
2.1 mm x 2.1 mm







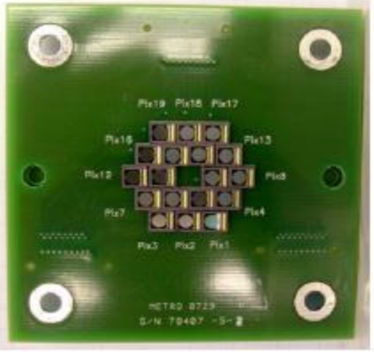
$$\frac{\text{muon signal}}{\text{rms noise}} \sim 12$$

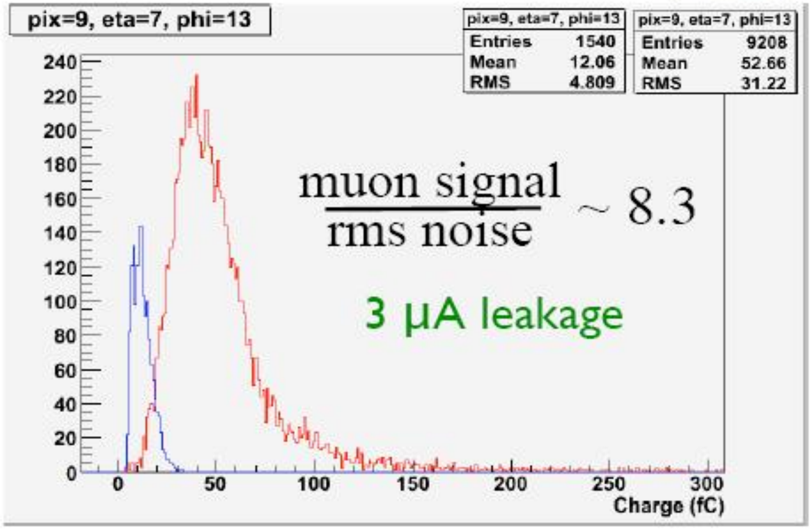


CPTA 2006
1764 pixels

2007: FBK-IRST SiPM

2.8 mm diam.





$$\frac{\text{muon signal}}{\text{rms noise}} \sim 8.3$$

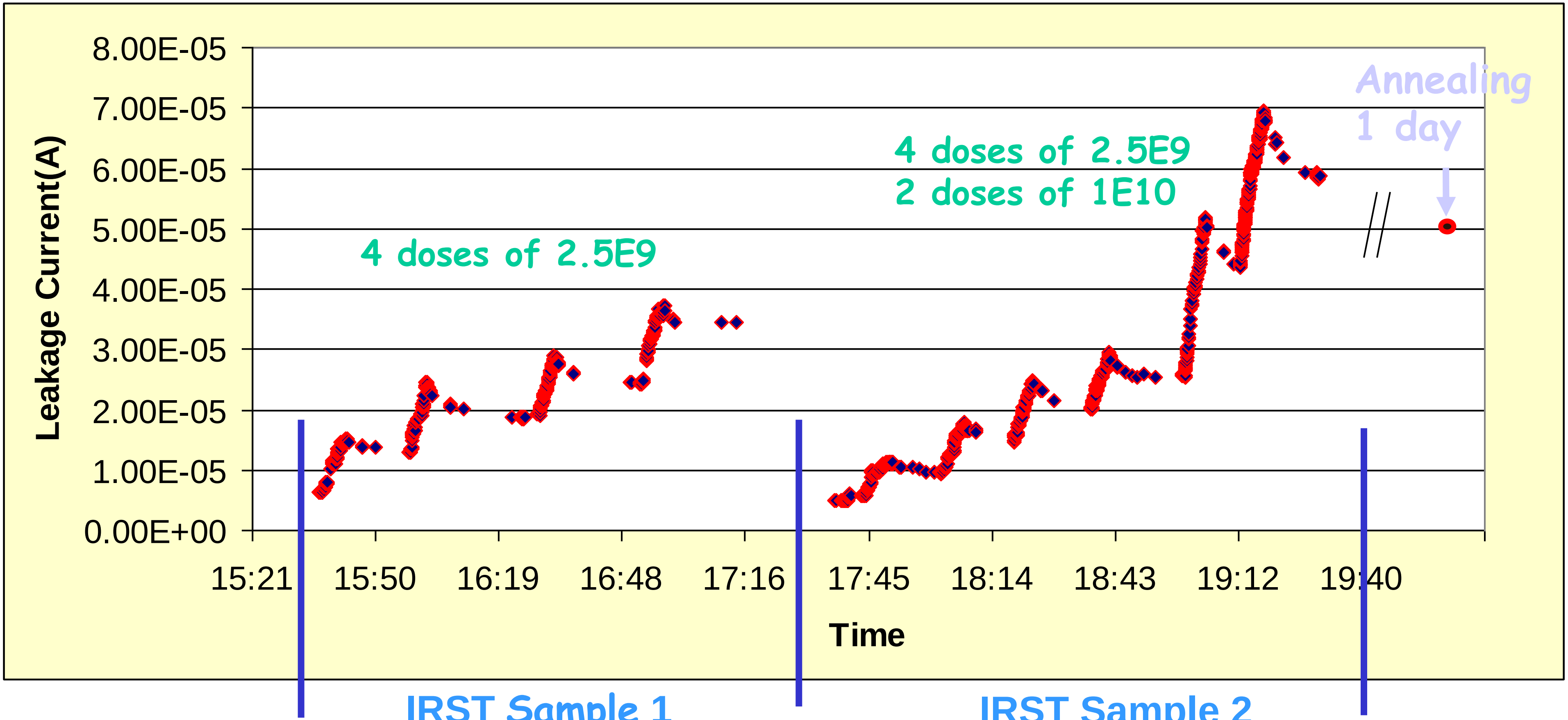
3 μA leakage

IRST

1250 pixels

Radiation damage for 240 MeV Protons

Custom 6 mm2 FBK SiPM



4 doses of 2.5E9

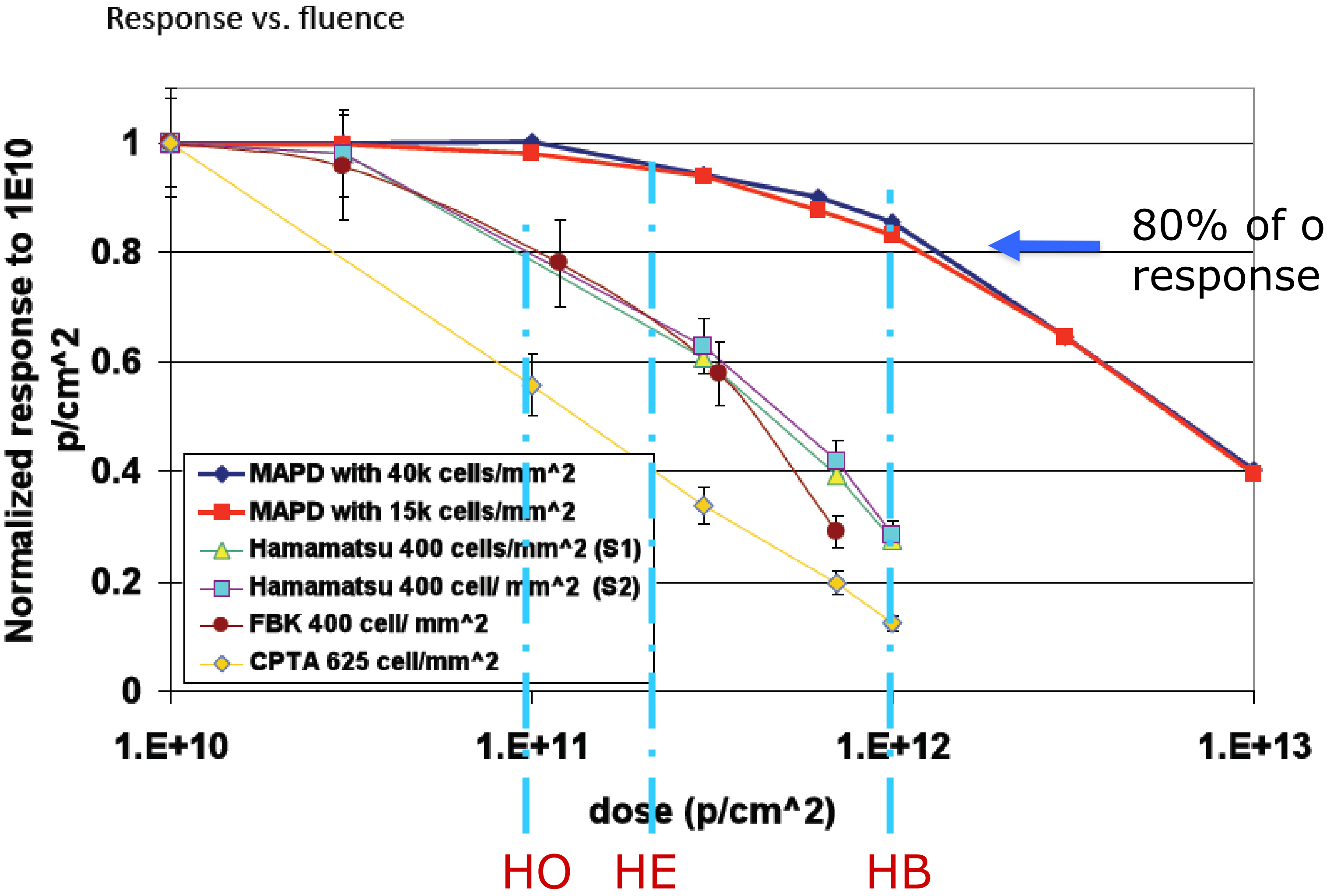
4 doses of 2.5E9
2 doses of 1E10

Annealing
1 day

IRST Sample 1
Total dose of 1E10 p/cm^2

IRST Sample 2
Total dose of 3E10 p/cm^2

SiPM Radiation Hardness Needs



80% of original response

SiPM improvement vs HPD

PDE: G-APD 30% vs HPD 12% at 520nm

Operation voltage: ~80V vs 8KV

disadvantage: Temperature dependance

concerns : Radiation damage

Linear Range

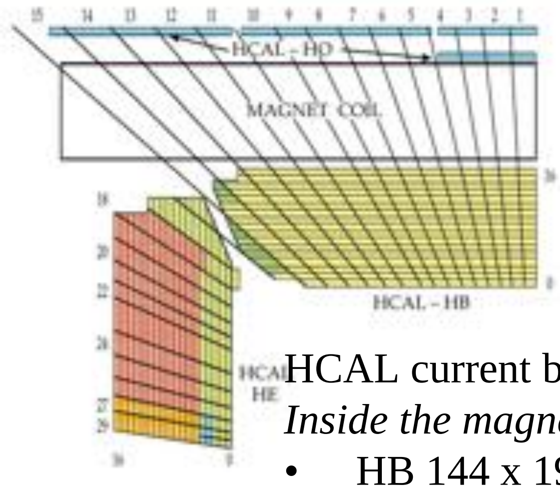
HPD readout => no segmentation

But fibers are coming from each layer and summed into 1 HPD pixel

Upgrade

64-Channel HB RMs

48-Channel HE RMs



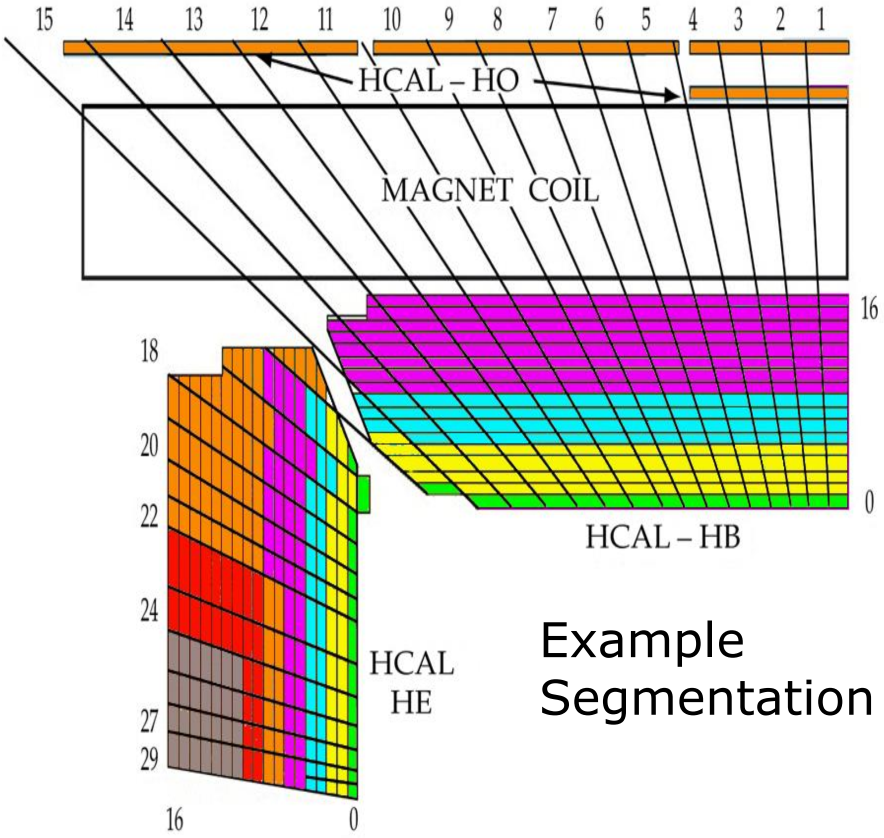
HCAL current baseline readout

Inside the magnet:

- HB 144 x 19 channel HPDs (16 layers)
- HE 144 x 19 channel HPDs (16 layers)

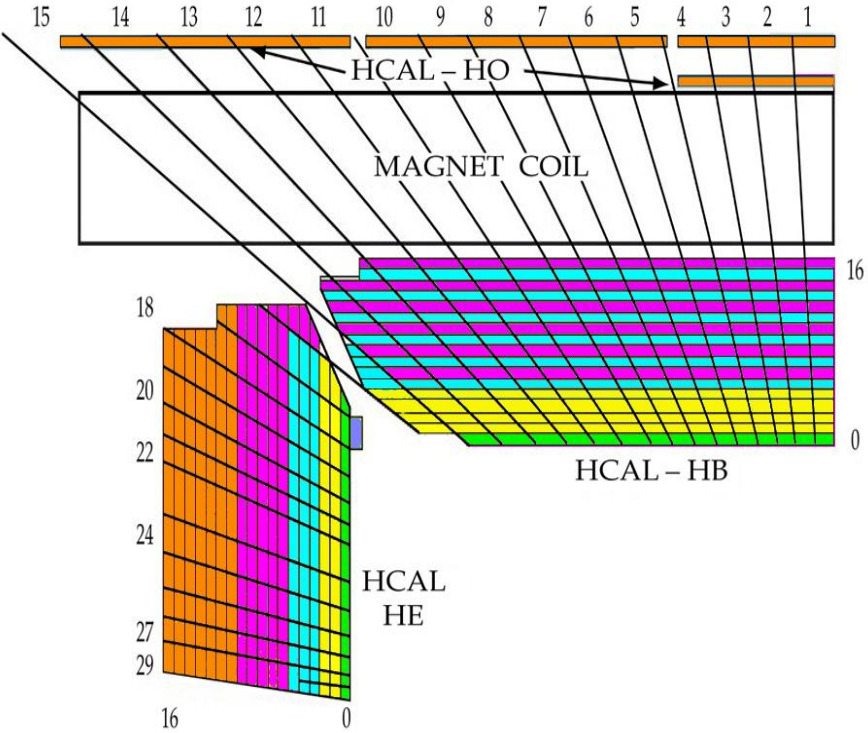
Outside the magnet:

- HO 132 x 19 channel HPDs (1-2 layers)
- HF 1800 one inch PMTs.



Example Segmentation

Segmentation (continue)



- HB Geometry:
  - High PU dependence in 1st layer (Green)
  - Large “Shower Max” deposition in 1st Interaction Length (Yellow)
  - Low Occupancy Rear Compartment (for muons) Interleaved to equalize signal and to provide redundancy (Purple/Blue)
- HE Geometry:
  - Higher Segmentation is possible due to lower phi granularity at high eta (above ieta=20)
  - Tuned for radiation recovery
  - Lepton Isolation @ High PU

SiPM Target Specifications for HCAL

- High PDE(515 nm): 15 - 30%
- Number of pixels (effective pixels): >15 000 1/mm^2
- Fast pixel recovery time: 5 – 100 ns (depends on the pixel density)
- Good radiation hardness > $3*10^{12}$ n/cm^2 (10 years of SLHC)
  - Gain*PDE change < 20%
  - noise < 1 MIP at 50 ns integration time
- Low optical cross-talk between cells <10%
- Low sensitivity to neutrons < 10^{-5} 1/n at 30 p.e. threshold?
- Low temperature coefficient < 5%/C
- High reliability

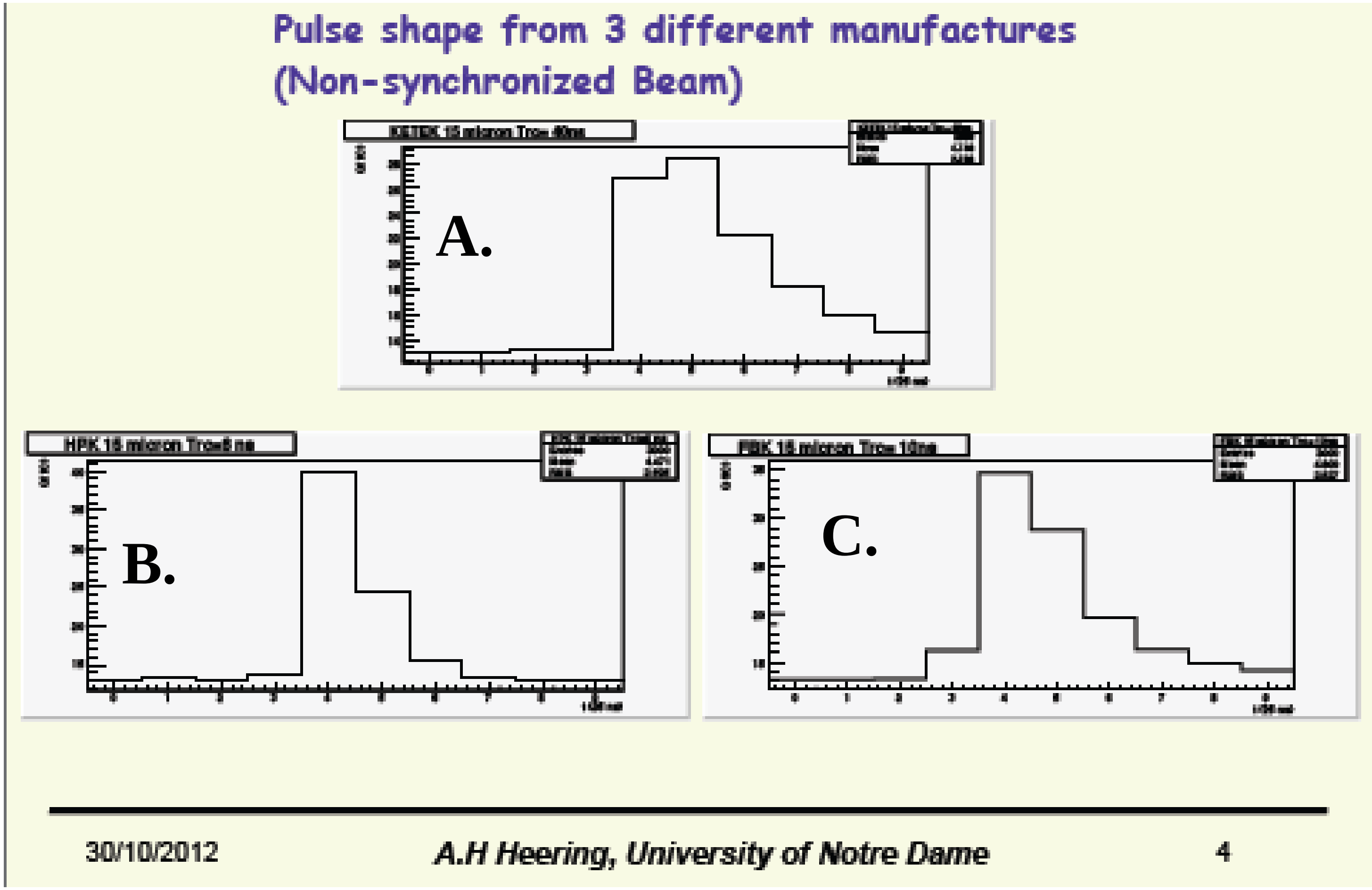
HCAL Measurements on 15 mm SiPM

October 2012 Test Beam

- *Response of 15mm SiPM (HPK – KETEK – FBK) in*
- *HCAL Test Beam (October 2012)*

- Excerpt from:
- H2 Test Beam and CERN PS Irrad
- activities for Phase 1 and 2 Upgrade
- *A.H Heering, University of Notre Dame*
- (Presented in HCAL Gen. Meeting Tuesday, October 30, 2012 and
- CMS Week, Tuesday, December 11, 2012)

150 GeV Muon Beam



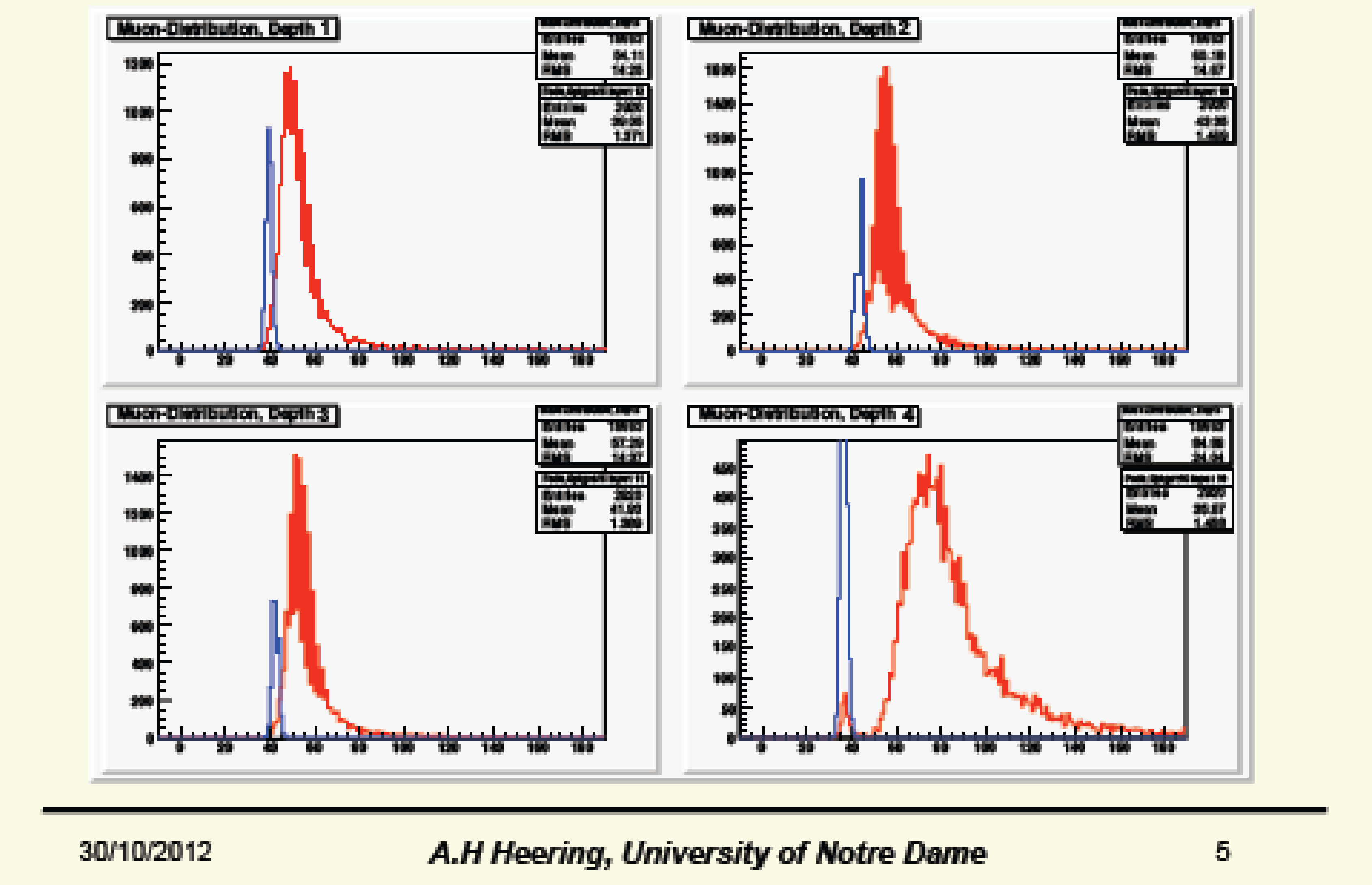
Pulse shape from 3 different manufactures
(Non-synchronized Beam)

30/10/2012 A.H Heering, University of Notre Dame 4

Charge (fC) distribution in 25ns time slices for:

- *A. KETEK; T_{rc} = 40ns*
- *B. HPK; T_{rc} = 6ns*
- *C. FBK; T_{rc} = 10ns*

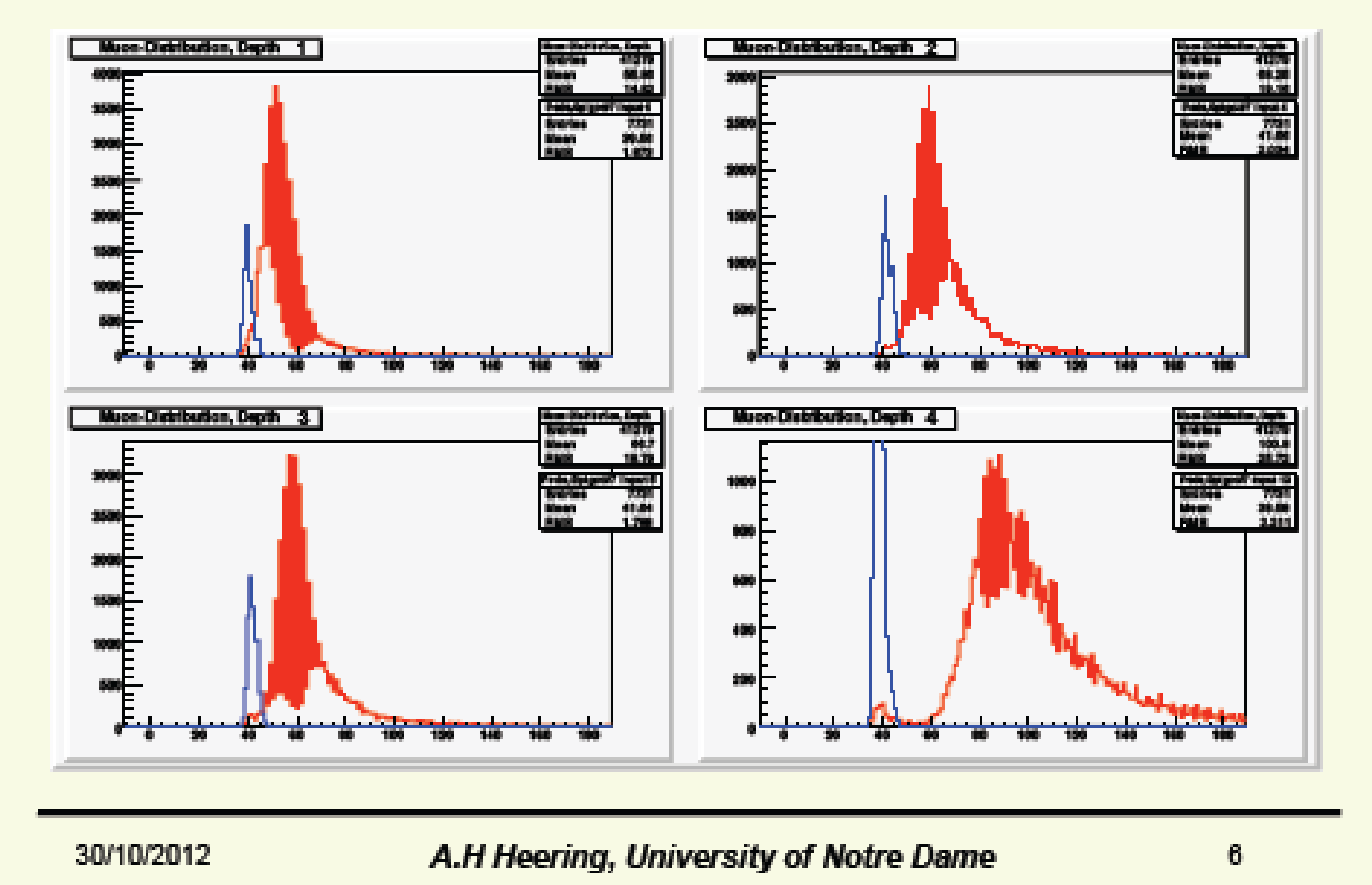
HPK – 150 GeV Muons in 4 depths



30/10/2012 *A.H Heering, University of Notre Dame* 5

- Blue : pedestal
- Red : muon signal

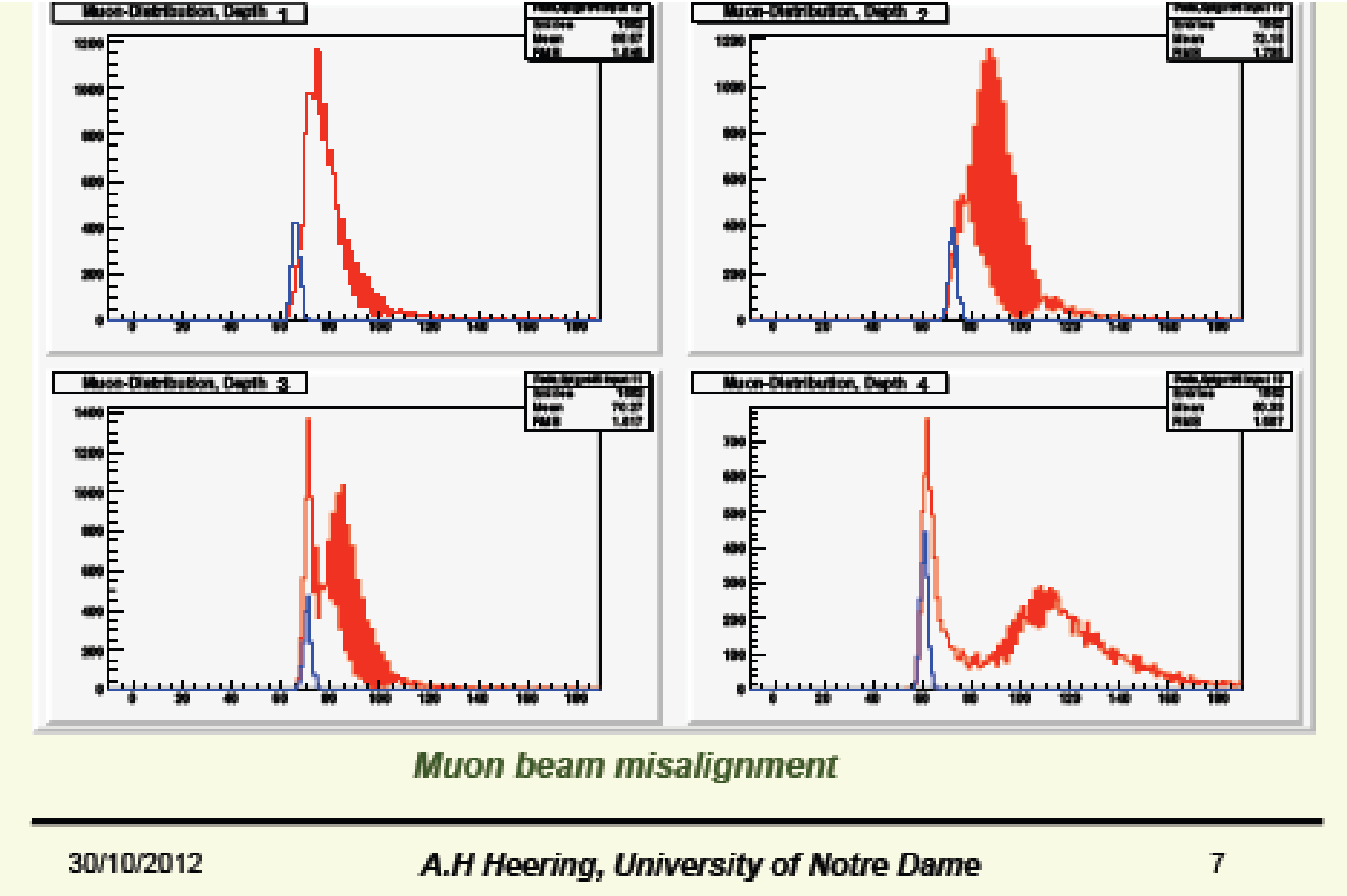
FBK – 150 GeV Muons in 4 depths



30/10/2012 *A.H Heering, University of Notre Dame* 6

- Blue : pedestal
- Red : muon signal

KETEK – 150 GeV Muons in 4 depths



Muon beam misalignment

30/10/2012

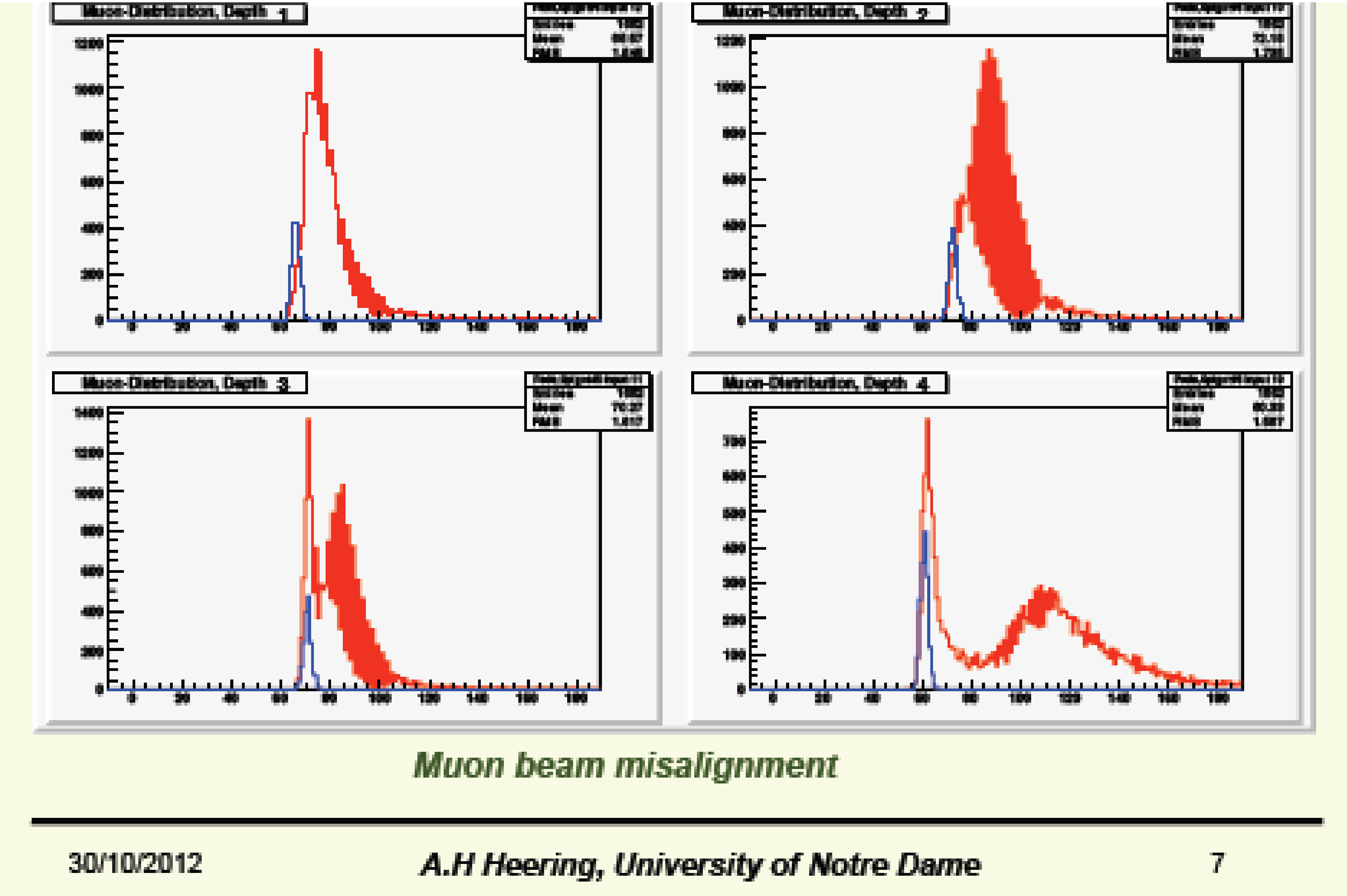
A.H Heering, University of Notre Dame

7

Blue : pedestal

Red : muon signal

KETEK – 150 GeV Muons in 4 depths



Muon beam misalignment

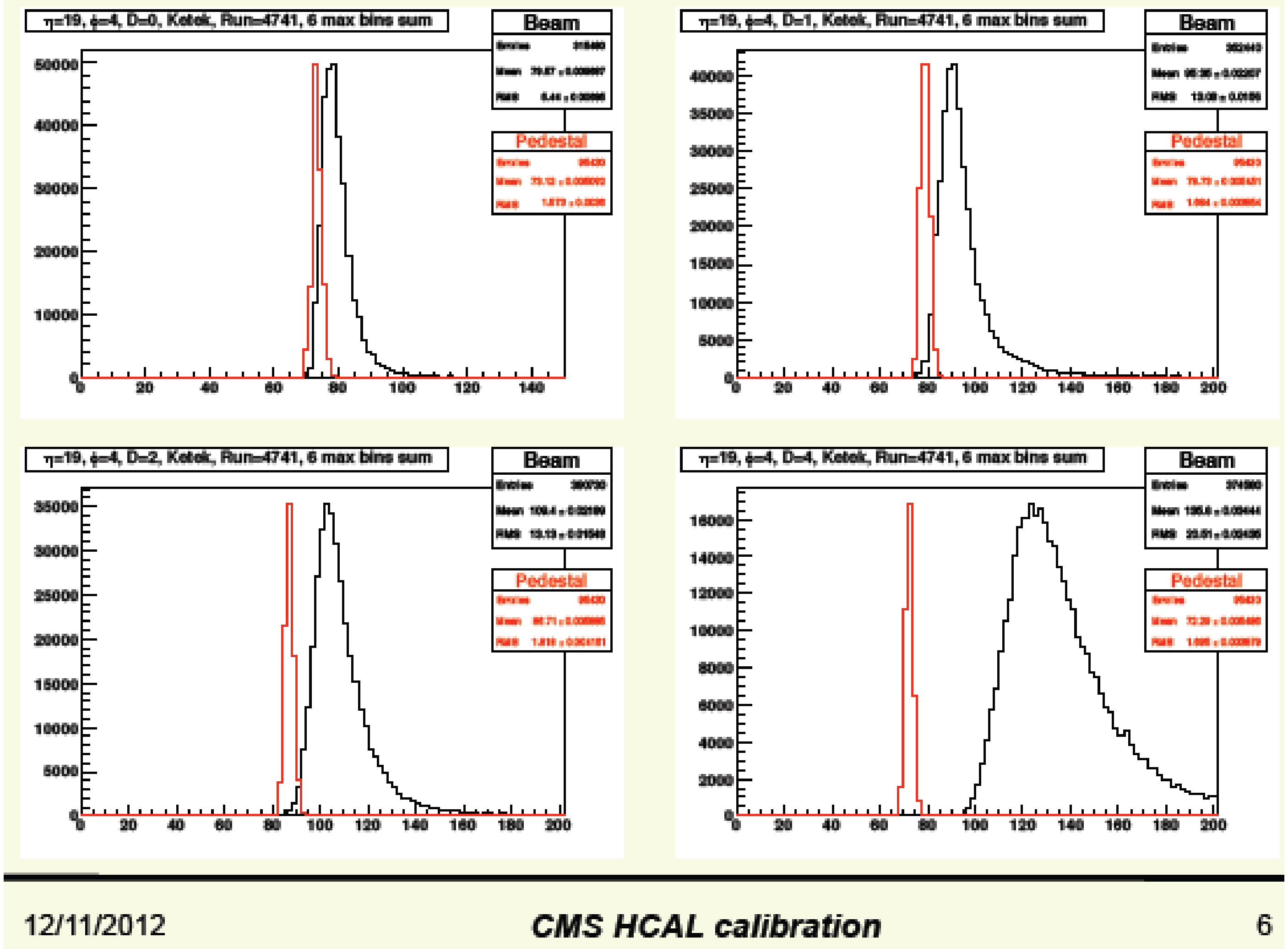
30/10/2012

A.H Heering, University of Notre Dame

7

Blue : pedestal
Red : muon signal

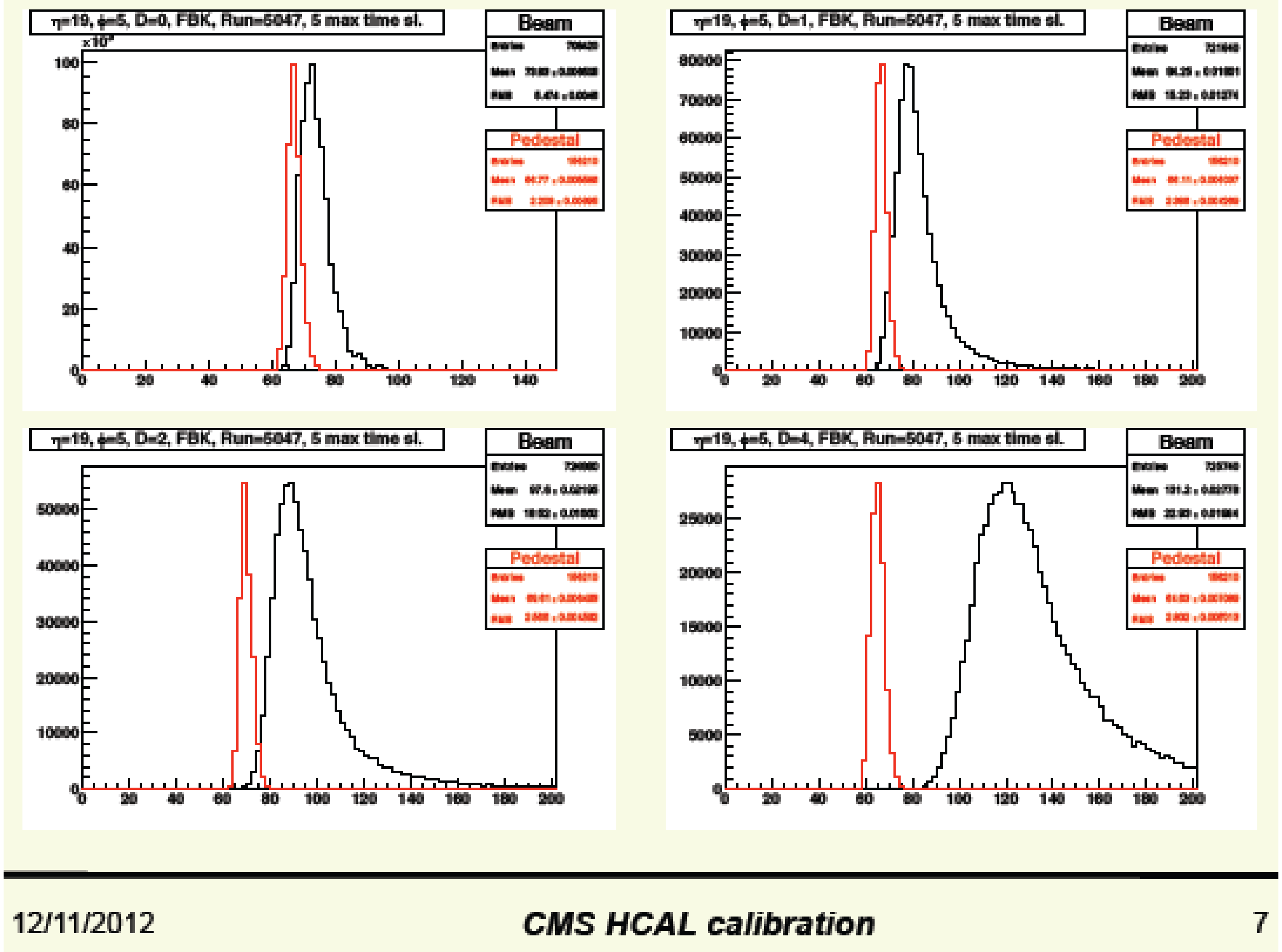
Ketek – 150 GeV Muons in 4 depths



12/11/2012 *CMS HCAL calibration* 6

- Red : pedestal
- Blue : muon signal

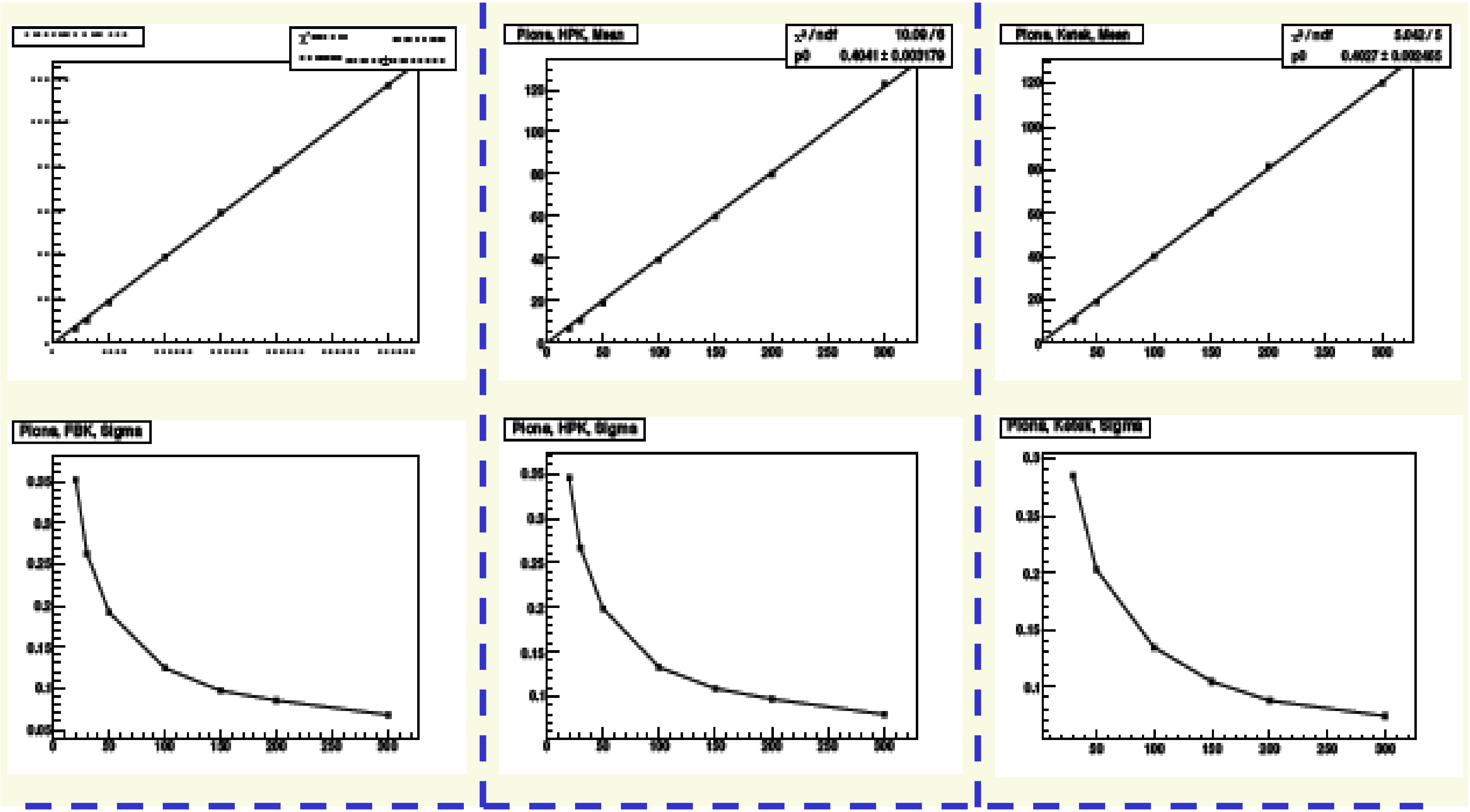
FBK – 150 GeV Muons in 4 depths



12/11/2012 *CMS HCAL calibration* 7

- Red : pedestal
- Blue : muon signal

Pions – Energy Scan

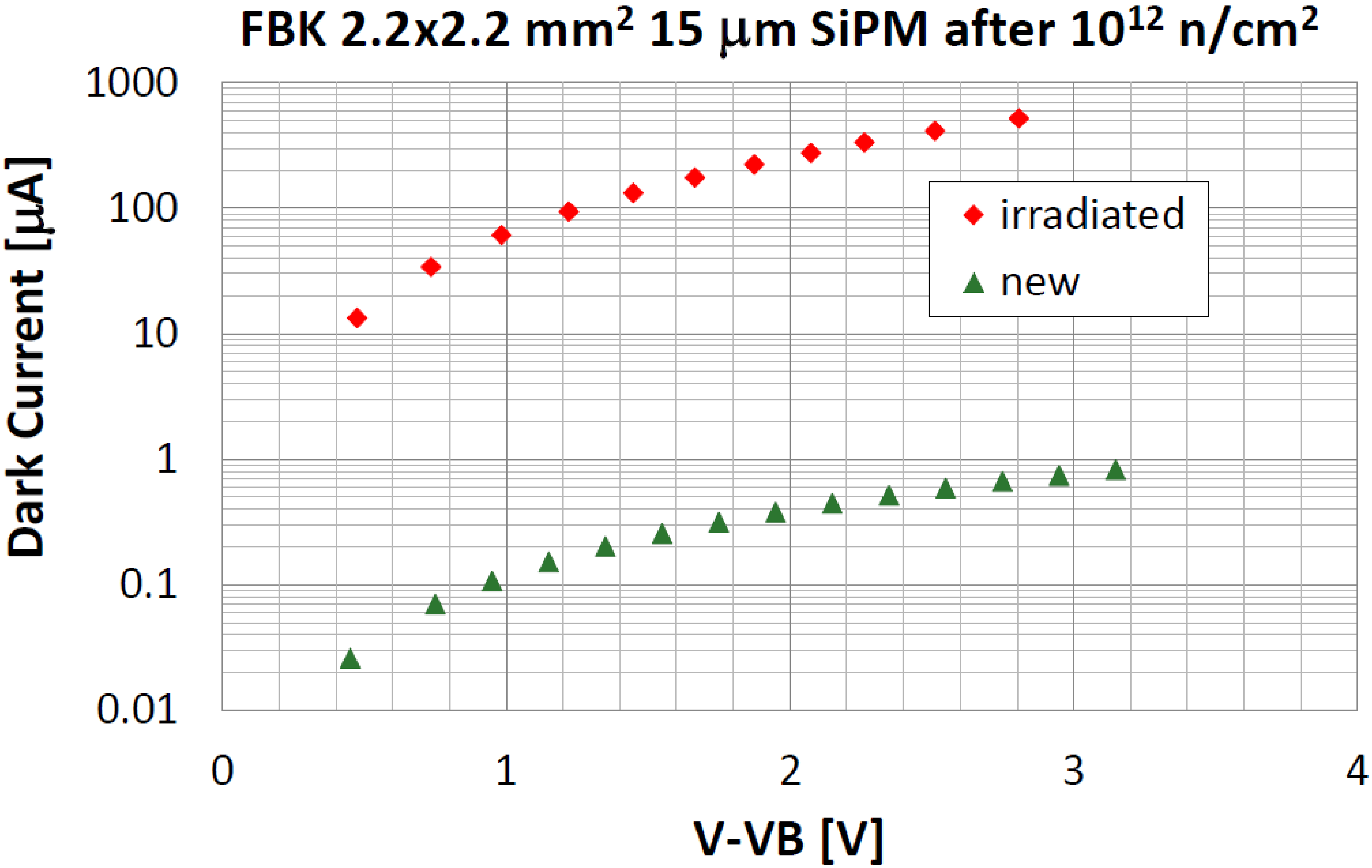


FBK

FBK

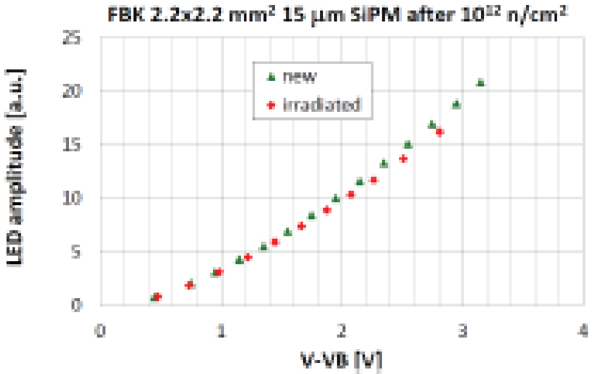
Ketek

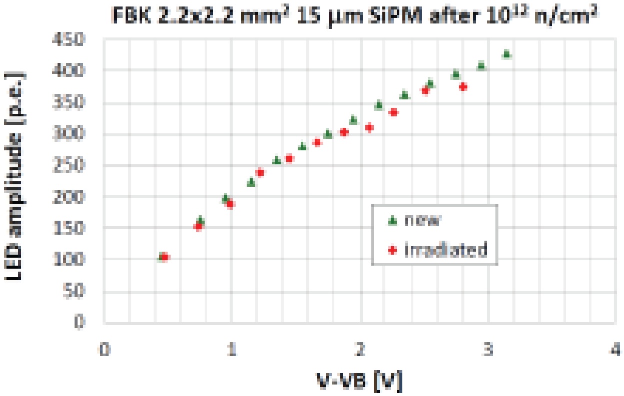
Radiation effects



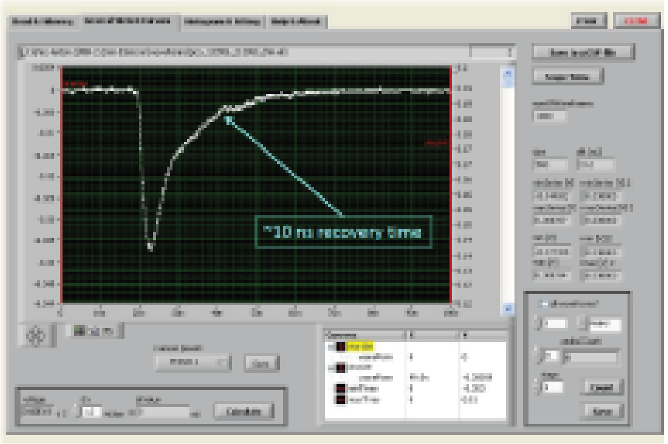
(continue)

Gain and PDE of the 2012 SiPM didn.t change after 1E12 neutrons/cm^2

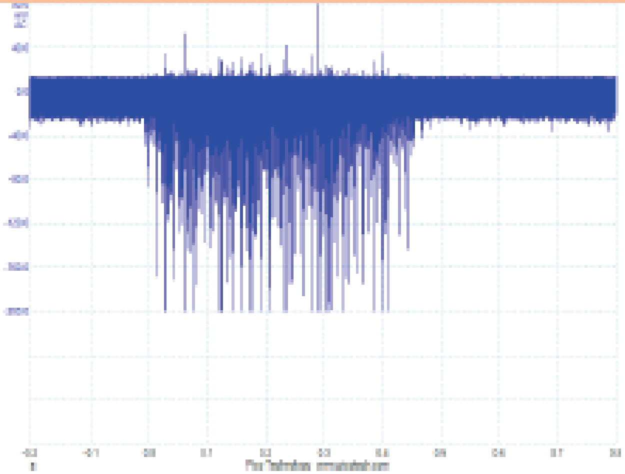




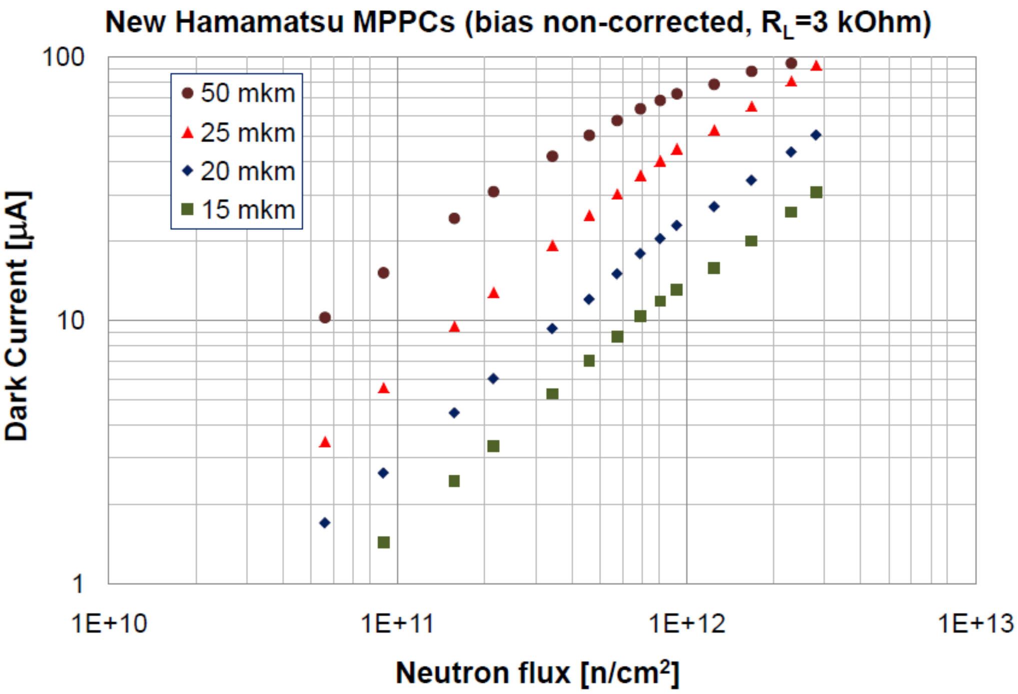
New FBK SiPM has very fast (<10 ns) cell recovery time



Neutron signals are seen with new FBK SiPMs.



Dark current vs. exposure to neutrons (Eeq~1 MeV) for different SiPMs



High energy neutrons/protons produce silicon defects which cause an increase in dark count and leakage current in SiPMs:

Id~α*Φ*V*M*k,

α–dark current damage constant [A/cm];

Φ –particle flux [1/cm2];

V –silicon active volume [cm3]

M –SiPMgain

k –NIEL coefficient

αSi~4*10-17A*cm after 80 min annealing

at T=60 C (measured at T=20 C)

No change of VB (within 50 mV accuracy)

- No change of Rcell(within 5% accuracy)

-Dark current and dark count significantly increased for all the devices

- For Hamamatsu MPPCs : deff~ 4 -8 µm

V~S*Gf*deff, S -areaGf-geometric factordeff-effective thickness

2013 R&D Goals for 3 vendors

2012 R&D results for 3 vendors (KETEK, FBK and Hamamatsu)

- SiPM photon detection efficiency for green light was improved from 10-15% up to 20-30 % for all the producers;
- •Sensitivity to fast neutrons was

significantly reduced for Hamamatsu MPPCs;

- Resistance to radiation was improved for all SiPMs
- equivalent noise in GeVs will be a factor of 1.5-2 lower with same neutron fluence

2013 R&D Goals

KETEK:
• Reduce cell recovery time from 44 ns to 5-8 ns
• Shift peak of PDE from 440 nm to 500-515 nm
• Reduce the gain to <2E5
FBK:
• Reduce sensitivity to neutrons;
• Improve radiation hardness;
• Reduce cell recovery time from 10 ns to 5-8 ns
• Reduce the gain to 2E5
Hamamatsu:
• Reduce sensitivity to neutrons
• Reduce cell recovery time from 10 ns to 5-8 ns
Develop new ceramic package for SiPM arrays (with glass/quartz window)

Plans and schedule

- 2013 : Complete R&D runs
- 2014 : Pre-production run and delivery 2015 : Main production run and delivery
- 2016-17: Assembling and testing
- 2018: Installing into CMS

Backups

More on compensation

Dual readout method, etc.

References

- Mark A Thomson, Particle flow calorimetry at the ILC. AIP Conf.Proc. 896 :215-224,2007.
- V.Andreev et al (CALICE), A high-granularity scintillator calorimeter readout with silicon photomultipliers NIM-PR A540 (2005) 368–380
- S. Abdullin et al. (CMS Collaboration) Design, performance, and calibration of CMS hadron-barrel calorimeter wedges Eur. Phys. J. C 55, 159–171 (2008)
- P.Bohn et al., Radiation damage studies of silicon photomultipliers NIM-PR A598(2009)722–736
- A. H. Heering et al., Radiation Damage Studies on SiPMs for Calorimetry at the Super LHC. 2008 IEEE Nucl. Science Symposium N12-6 p. 1523 sgg

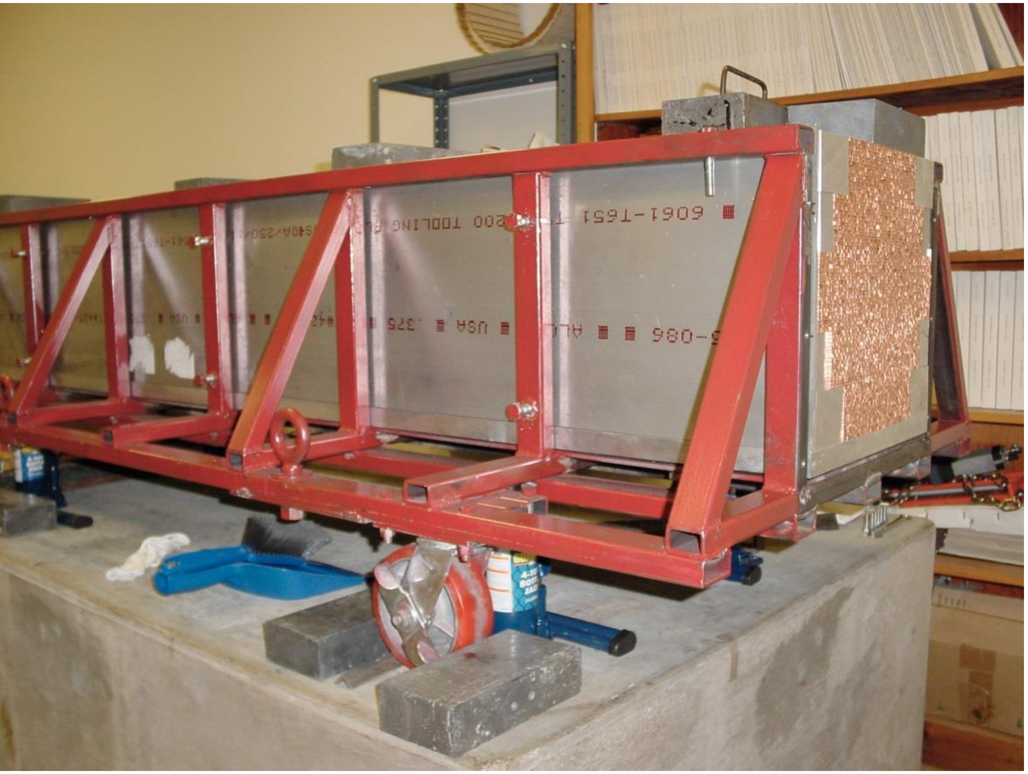
Compensation by dual readout method

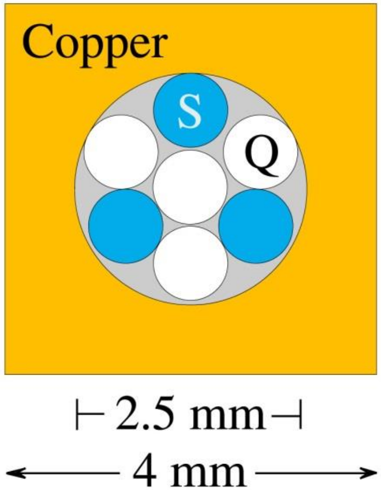
Main theme: multiple measurements of every shower to suppress fluctuations (R. Wigmans *et al.*)

•Spatial changes in density of local energy deposit	•fine spatial sampling with SciFi every 2mm	•Like SPACAL
•Fluctuations in EM fraction of total shower energy	•clear fibers measuring only EM component of shower via Cherenkov light from electrons ($E_{th} = 0.25$ MeV)	•Like HF
•Binding energy losses from nuclear break-up	•measure MeV neutron component of shower.	• Triple Readout

DREAM = SPACAL + HF

DREAM [Dual REAdout Module] prototype is 1.5 ton heavy





(S, Q fibers
0.8 mm ϕ)

Cell

[basic element of detector]

2m long extruded copper rod, [4 mm x 4 mm]; 2.5mm hole contains 7 fibers:3 scintillator & 4 quartz(or acrylic plastic).

In total, 5580 copper rods (1130Kg) and 90 km optical fibers.

Composition (volume) Cu: S : Q : air = 69.3 : 9.4 :12.6 : 8.7 (%)

Effective Rad. length (X_0)=20.1mm;Moliere radius(r_M)=20.35mm
Nuclear Inter. length (λ_{int})=200mm;10 λ_{int} depth Cu.

Filling fraction = 31.7%; Sampling fraction = 2.1%

Determining f_{em}

Mockett 1983 SLAC Summer Institute

A technique is needed that is sensitive to the relative fraction of electromagnetic energy and hadronic energy deposited by the shower.
This could be done hypothetically if the energy were sampled by two media: one which was sensitive to the beta equals one electrons and another which was sensitive to both the electrons and other charged particles. For example one sampler could be lucite which is sensitive only to the fast particles, while the other sampler could be scintillator.
Then the fraction of pizeros produced could be determined from the relative pulse heights
of the two samplers. Another technique might be to utilize the slow scintillation pulse and the fast Cerenkov pulse in total absorbing materials such as scintillating glass or Barium fluoride. By appropriate gating for wave form sampling …”

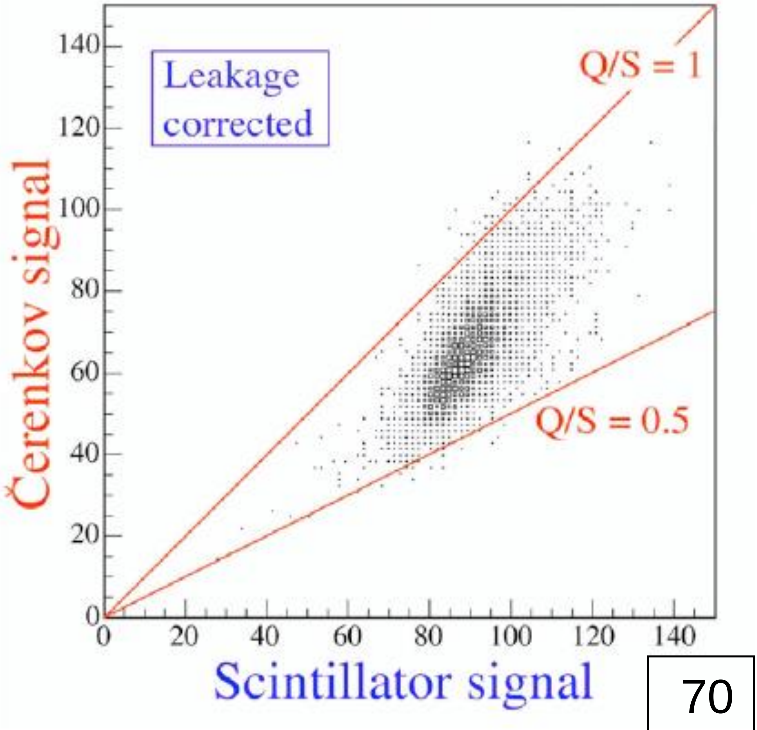
Thanks to Erik Ramberg for this reference.

$$S = E\left[f_{\mathrm{em}} + \frac{1}{(e/h)_S}(1 - f_{\mathrm{em}})\right]$$

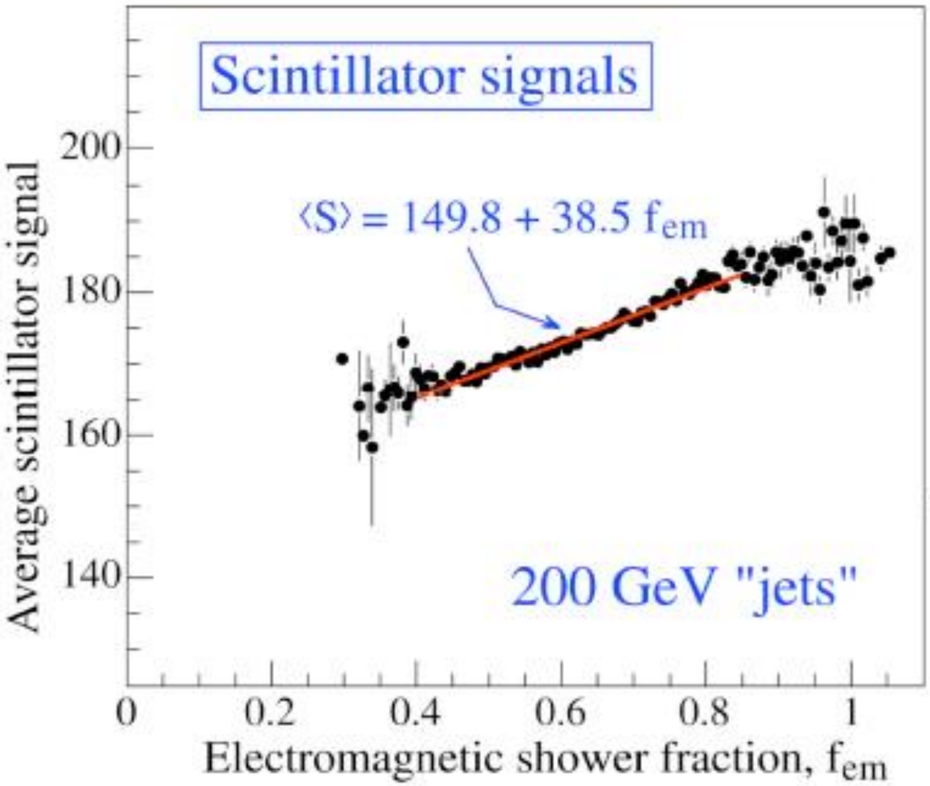
$$Q = E\left[f_{\mathrm{em}} + \frac{1}{(e/h)_Q}(1 - f_{\mathrm{em}})\right]$$

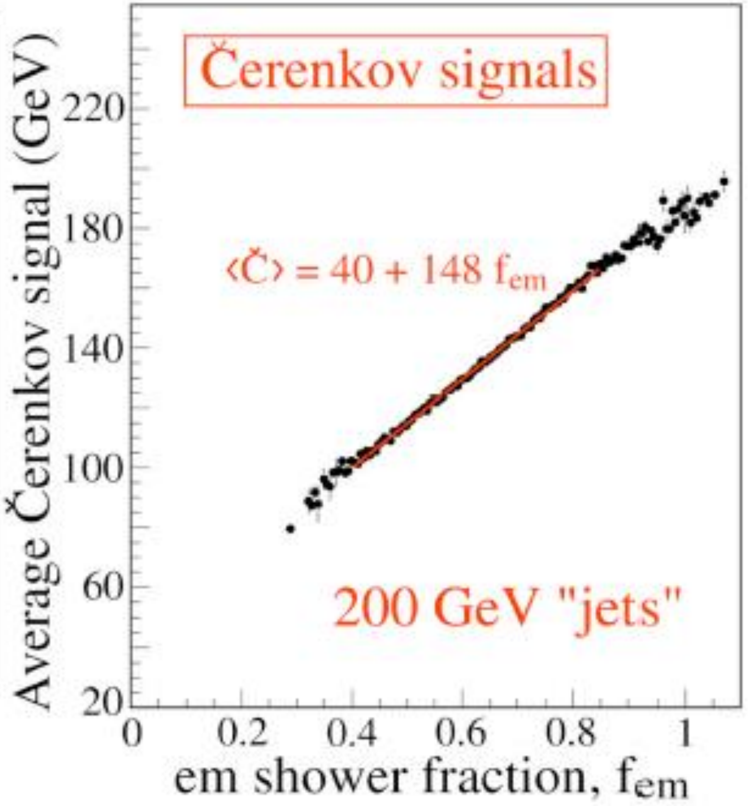
$e.g.$ If $e/h = 1.3$ (S), 5 (Q)

$$\boxed{\frac{Q}{S} = \frac{f_{\mathrm{em}} + 0.20\ (1 - f_{\mathrm{em}})}{f_{\mathrm{em}} + 0.77\ (1 - f_{\mathrm{em}})}}$$



DREAM: Signal dependence on f_{em}





$$\boxed{R(f_{\mathrm{em}}) = p_0 + p_1 f_{\mathrm{em}}} \quad \text{with} \quad \boxed{\frac{p_1}{p_0} = e/h - 1}$$

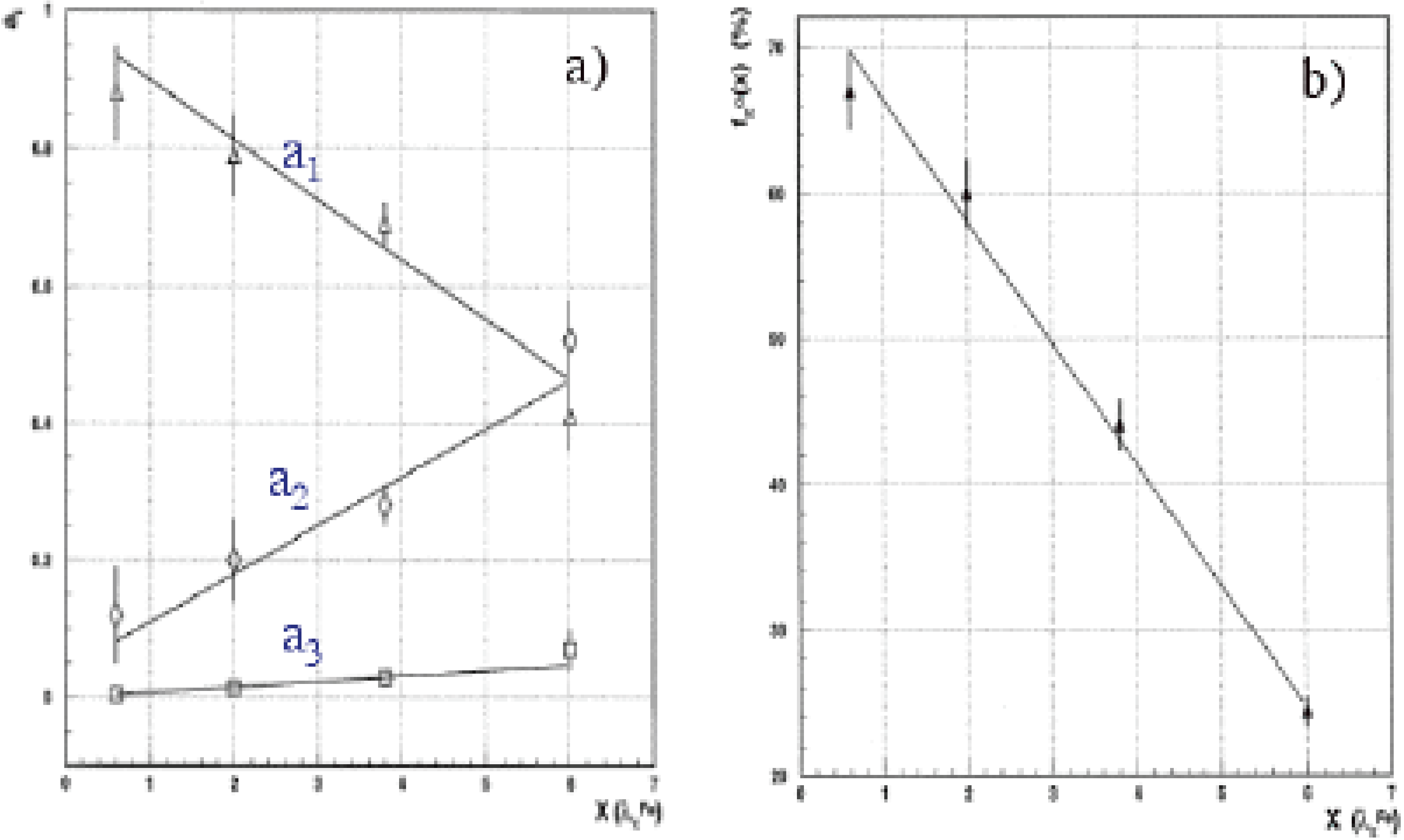
Cu/scintillator e/h = 1.3 Cu/quartz e/h = 4.7

From:
NIM A537 (2005) 537

Evolving Dual Readout Concepts

- *Homogeneous totally active:*
  - *Absorber and Cerenkov radiator are the same: f.i. heavy glass*
  - *Scintillator can be fibers or liquid in heavy glass tubing*
  - *First test this year at FNAL*
- *All- Xstal calorimeter, acting both as scintillator, Cherenkov radiator and absorber! S and C photons are discriminated by pulse shape,… polarization?*

Shower depth development



FACTOR Project

[Walter Bonvicini *et al.*: Messina, Roma, Trieste, Udine + FBK/irst]

- FBK-IRST has long-standing collaboration with INFN in the field of Si detectors
- Within FBK/irst - INFN agreement, a (3-year) project (FACTOR) aims at establishing SiPMs as choice devices for (dual) readout of (compensating) hadron calorimeters.

SiPMs development at FBK-irst started in 2005