Progress from CALICE

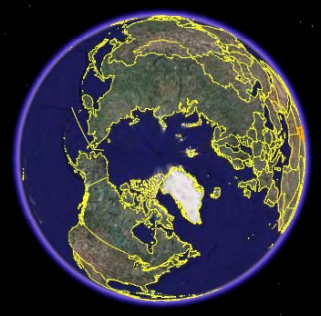
Calorimeter for ILC

Emphasis on test beam results

José Repond
Argonne National Laboratory

LCWS 2007, DESY, May 30 – June 3, 2007

Members of the CALICE Collaboration

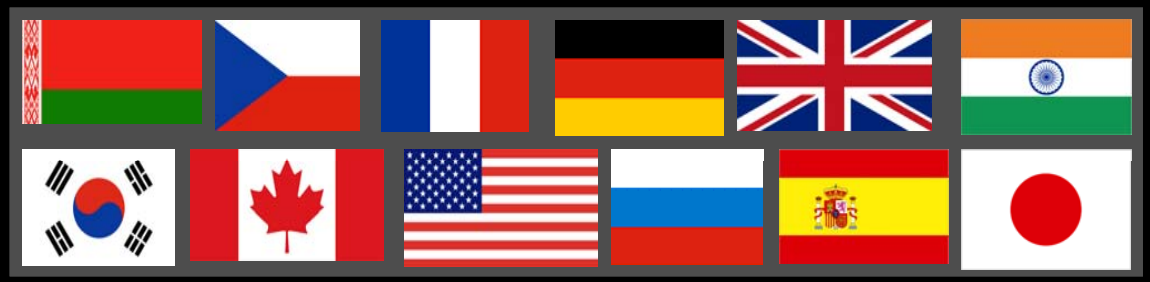


3 regions

12 countries

41 institutes

> 200 physicists



Goals of the Collaboration

To provide a basis for choosing a **calorimeter technology** for the ILC detectors

To **measure** electromagnetic and hadronic showers with unprecedented granularity

Physics prototypes

Various technologies (silicon, scintillator, gas)
Large cubes (1 m^3 HCALs)
Not necessarily optimized for an ILC calorimeter
Detailed test program in particle beams

Technical prototypes

Various technologies
Can be only partially equipped
Appropriate shapes (wedges) for ILC detectors
All bells and whistles (cooling, integrated supplies…)
Detailed test program in particle beams

To **advance** calorimeter technologies and our **understanding** of calorimetry in general

To design, build and test **ILC calorimeter prototypes**

CALICE Projects and the Concepts

CALICE Projects	
ECALs	Silicon - Tungsten
	MAPS - Tungsten
	Scintillator - Lead
HCALs	Scintillator - Steel
	RPCs - Steel
	GEMs- Steel
	MicroMegas - Steel
TCMTs*	Scintillator - Steel

Detector Concept	Optimized for PFA	Compensating Calorimetry (hardware)
SiD	Yes	No
LDC	Yes	No
GLD	Yes	Yes
4th	No	Yes

All calorimeters with very fine segmentation of the readout

* Tail catcher and Muon Tracker

PFAs and Calorimetry

Fact

Particle Flow Algorithms improve energy resolution compared to calorimeter measurement alone (see ALEPH, CDF, ZEUS…)

How do they work?

Particles in jets	Fraction of energy	Measured with	Resolution [σ^2]
Charged	65 %	Tracker	Negligible
Photons	25 %	ECAL with 15%/√E	$0.07^2\ E_{jet}$
Neutral Hadrons	10 %	ECAL + HCAL with 50%/√E	$0.16^2\ E_{jet}$
Confusion	The real challenge		**≤ 0.04²** (goal)

} 18%/√E

Minimize confusion term

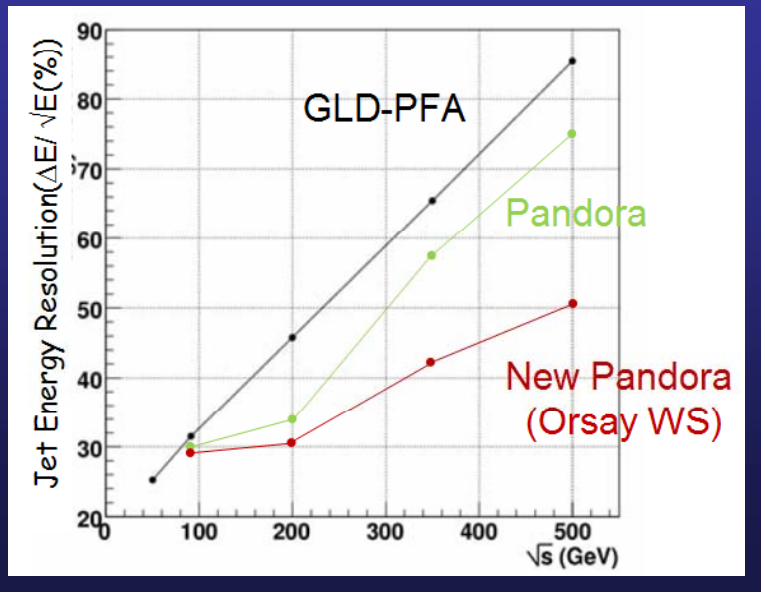
Maximize segmentation of the calorimeter readout

High segmentation

O(<1 cm²) in the ECAL
O(~1 cm²) in the HCAL
→ O(10^7 – 10^8) channels for entire ILC calorimter

Can PFAs achieve the ILC goal?

YES!



Status of the various projects

Calorimeter	Technology	Detector R&D	Physics Prototype	Technical Prototype
ECALs	Silicon - Tungsten	Well advanced	Exposed to beam	Design started
	MAPS - Tungsten	Started		
	Scintillator - Lead	Well advanced	Exposed to beam	
HCALs	Scintillator - Steel	Well advanced	Exposed to beam	Design started
	RPCs - Steel	Well advanced	Almost ready to be build	(Design started)
	GEMs- Steel	Ongoing		
	MicroMegas - Steel	Started		
TCMTs	Scintillator - Steel	Well advanced	Exposed to beam	

Will concentrate on these in the following…

Collaboration → Advantages

Shared hardware

e.g. Si-ECAL/Scint-HCAL use same electronic readout system
One steel plate stack and movable stage for all HCALs
Shared mechanical structure for Si- and MAPS-ECAL

Shared software

All projects use the same DAQ software

Shared test beams

DESY group helped ECALs when testing at DESY
One test beam effort at CERN involving Si-ECAL, Scint-HCAL, TCMT

Facilitates combined tests

e.g. Si-ECAL+Scint-HCAL+TCMT at CERN in 2006/2007
ECALs+HCALs+TCMT at FNAL in 2008/2010

Shared knowledge

CALICE meetings (3/year) are an excellent forum to report/discuss progress/ideas

CALICE Test Beam Activities

2006 – Fall 2007

DESY electrons 1 – 6 GeV

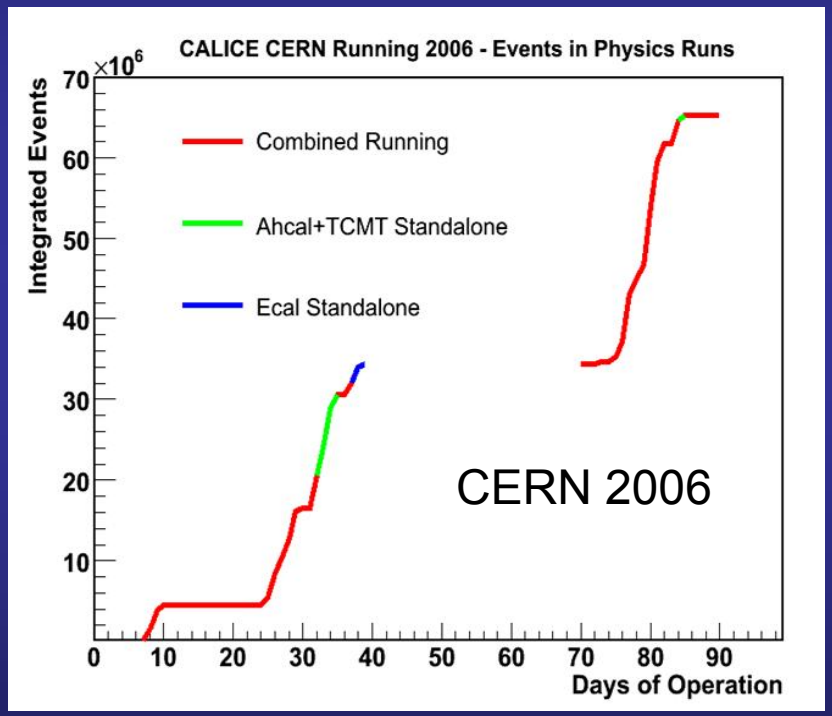
Silicon-ECAL
Scintillator ECAL
Scintillator HCAL
TCMT

CERN electrons and pions 6 – 120 GeV

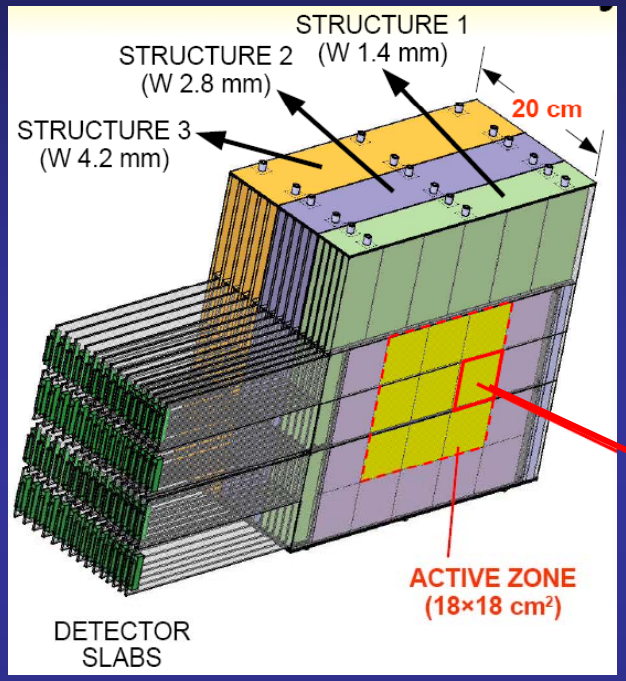
Silicon-ECAL
Scintillator HCAL
TCMT (complete)

FNAL protons at 120 GeV

3 RPCs
1 GEM
10 RPCs+4 GEMs



Silicon-Tungsten ECAL



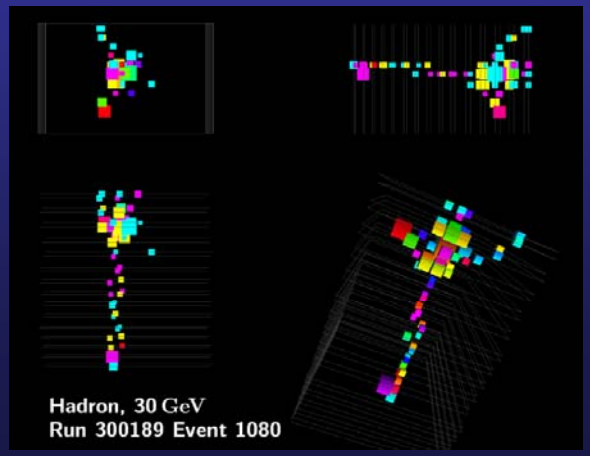
1 X_0(W) = 3.5 mm

Physics prototype

3 structures with different W thicknesses
30 layers; 1 x 1 cm^2 pads
12 x 18 cm^2 instrumented in 2006 CERN tests
→ 6480 readout channels

Tests at DESY/CERN in 2006

Electrons 1 – 45 GeV
Pions 6 – 120 GeV

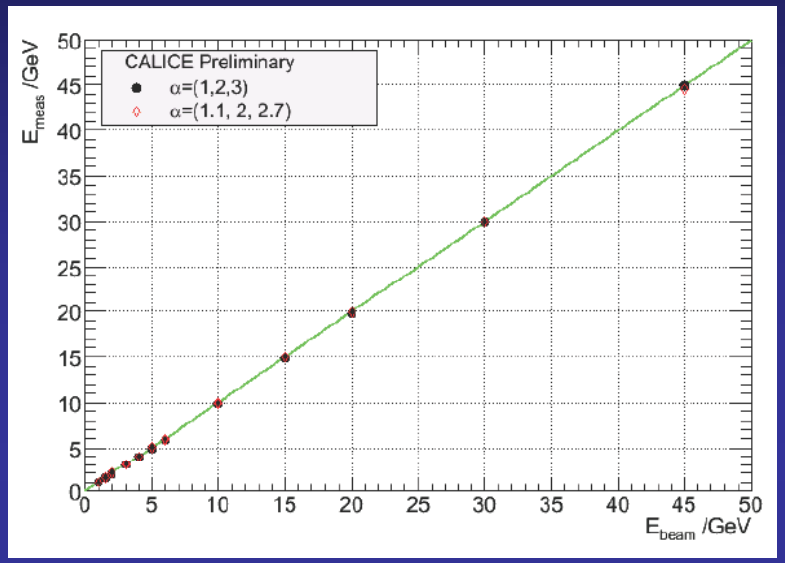


Electronic Readout

Front-end boards located outside of module
Digitization with VME – based system (off detector)

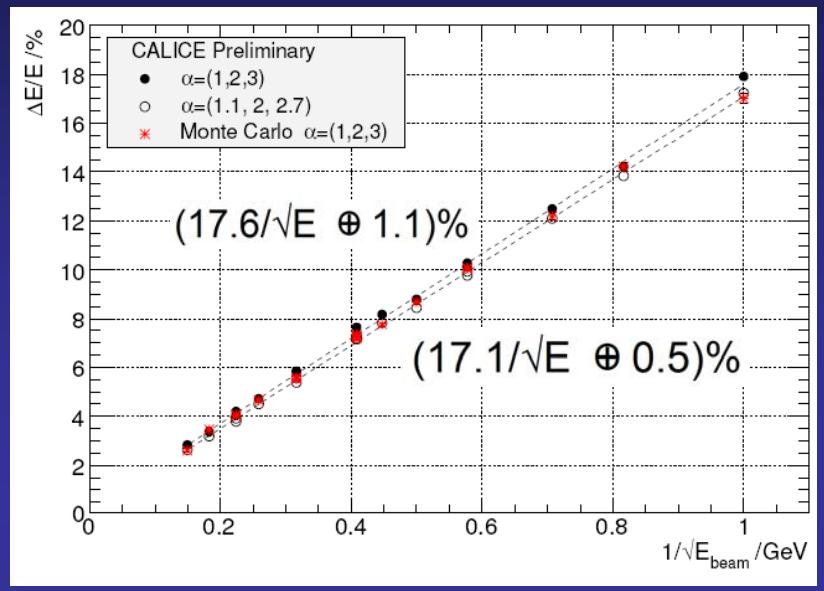
Linearity with electrons

Two different weighting schemes
Non-linearity at the 1% level



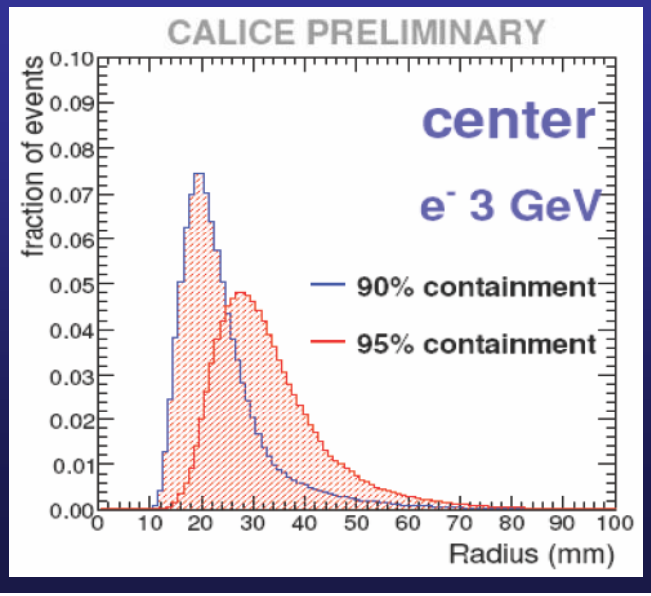
Resolution with electrons

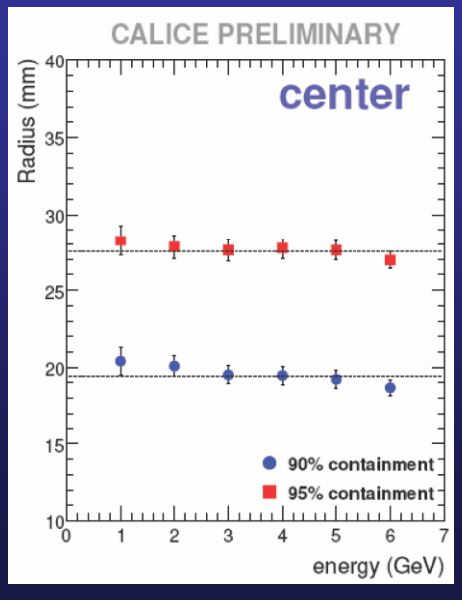
Close to expectation from MC



Transverse shower profile

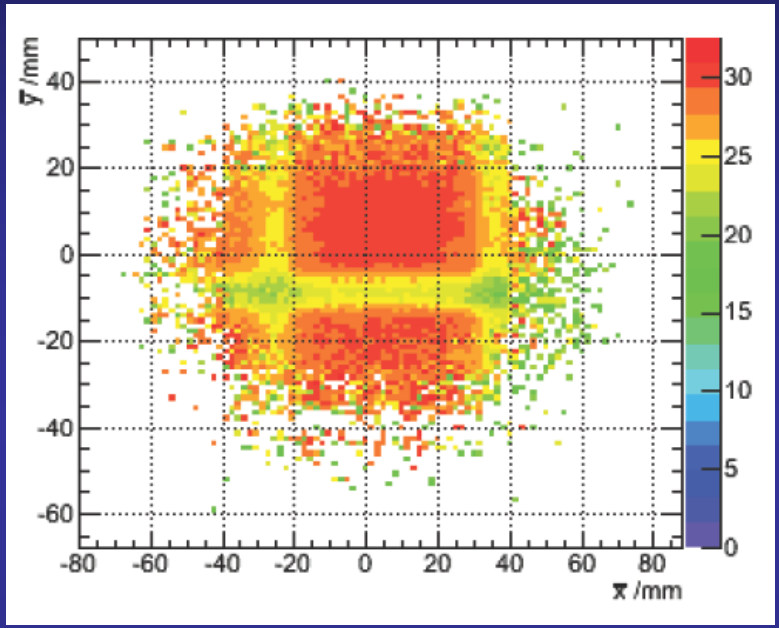
Moliere radius R_M contains
90% of EM shower energy
independently of energy
R_M (W) = 9 mm
Gap will increase $R_M(W) \rightarrow R_M^{eff}$

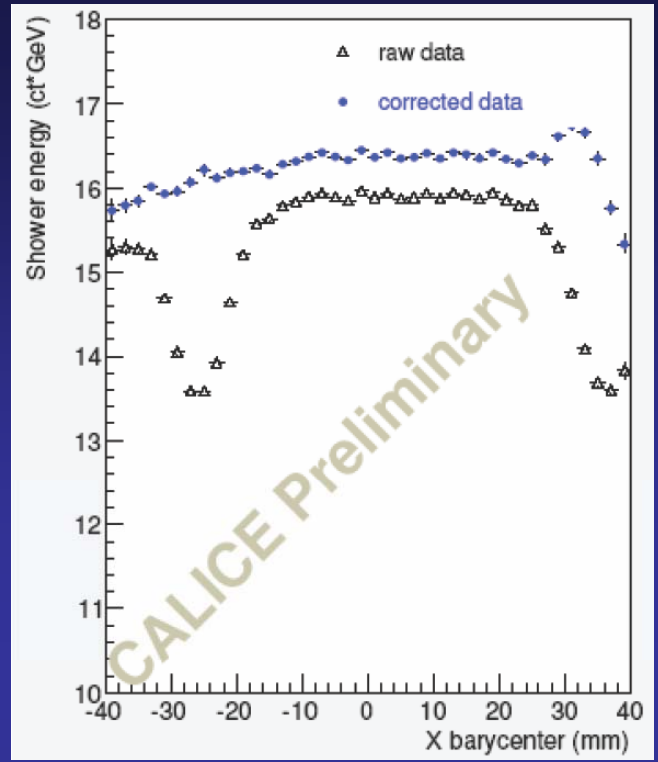




Study of inter-wafer gaps

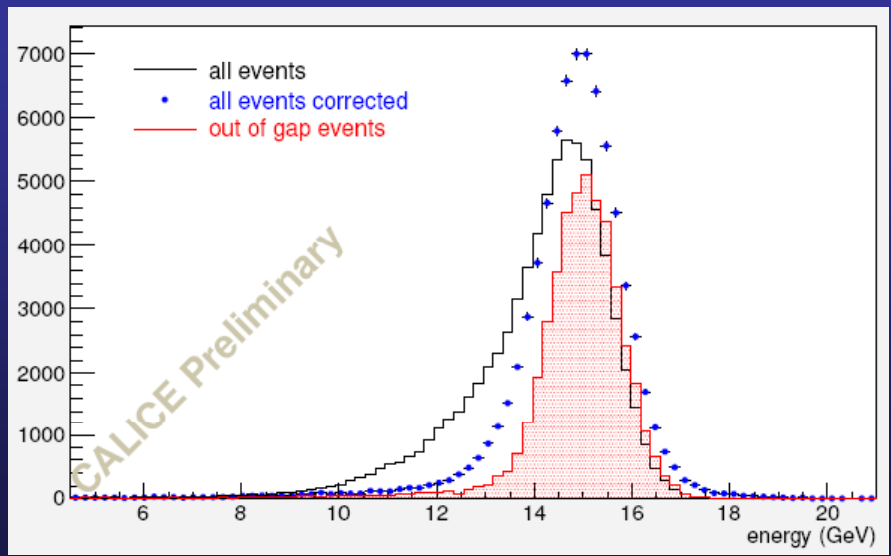
Decrease in response in both x and y ~ 12 %
Developed a correction procedure



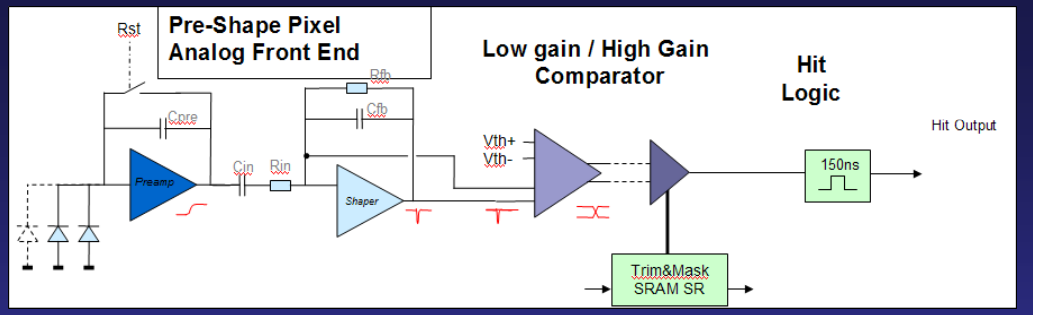


Effect on resolution

Correction improves resolution
→ eliminates asymmetric tail
Resolution away from gap still better



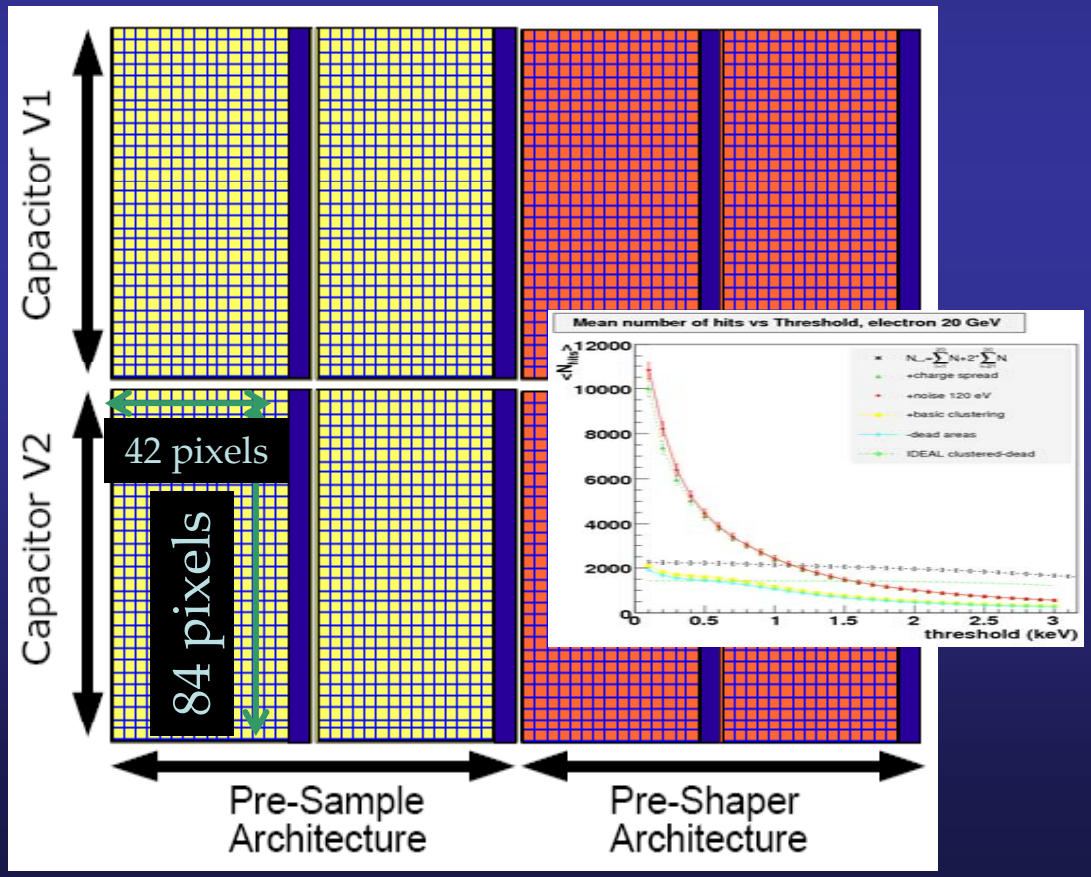
MAPS ECAL



Monolithic Active Pixel Detectors

In-pixel comparator and logic
50 x 50 μm^2 pixels
$\rightarrow 10^{12}$ pixels for the ECAL

} Digital (single-bit) readout



Test Sensor

Area of 1 x 1 cm^2 → ~ 28,000 pixels
Testing two different architectures

Pre-shape pixel analog front-end
Pre-sample pixel analog front-end

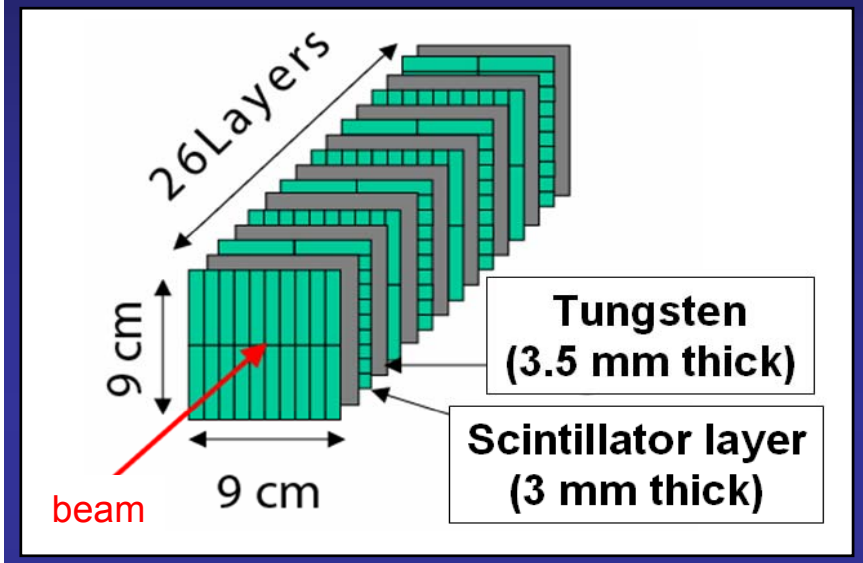
Submitted in April → In hand by July

Extensive simulation studies

Charge collection effects
Resolution versus threshold
….

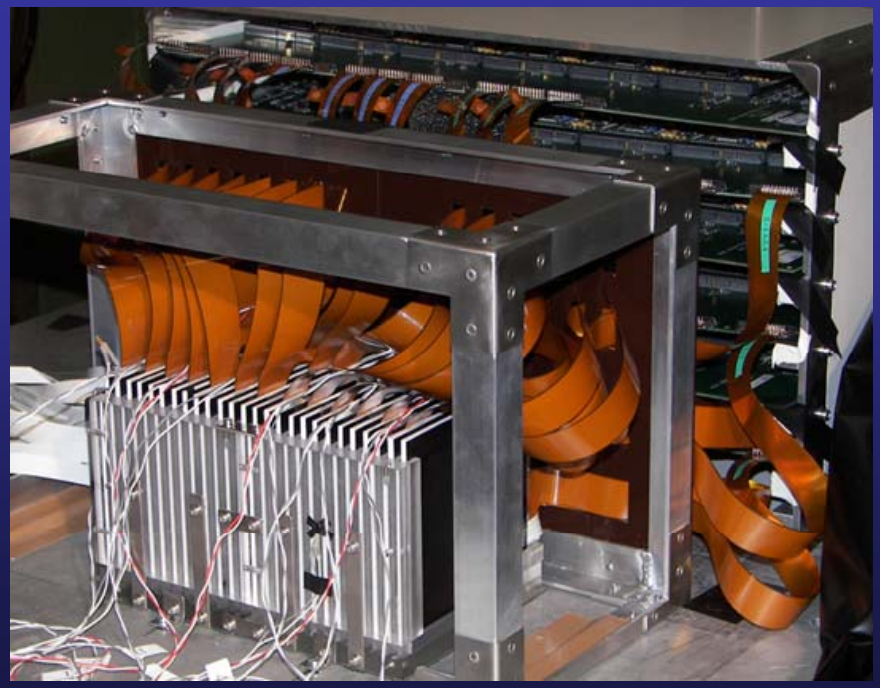
Scintillator-Tungsten ECAL

Offers the possibility of hardware compensation



Physics prototype

26 layers
1 x 4.5 x 0.3 cm^3 scintillator strips
Read out with Hamamatsu MPPCs
+ Scintillator-HCAL electronics

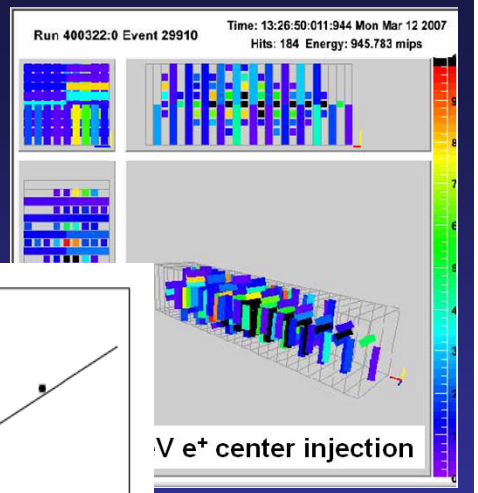


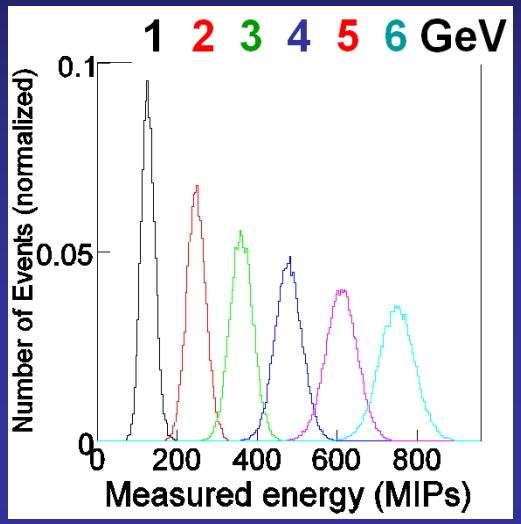
Tested different set-ups

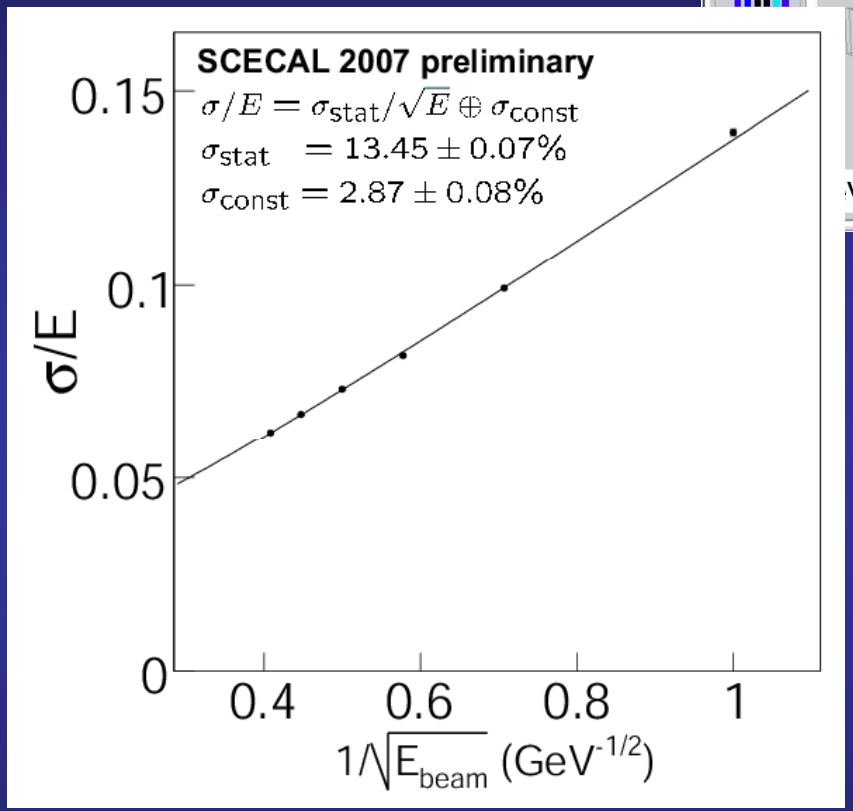
WLSF and groves
No WLSF (direct coupling)
WLSF in extruded scintillator

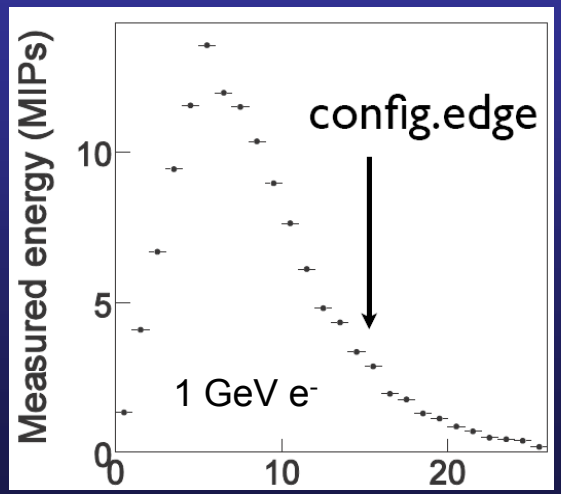
Tests in DESY electron beam: 1 – 6 GeV

Data taking in April 2007
→ Preliminary results







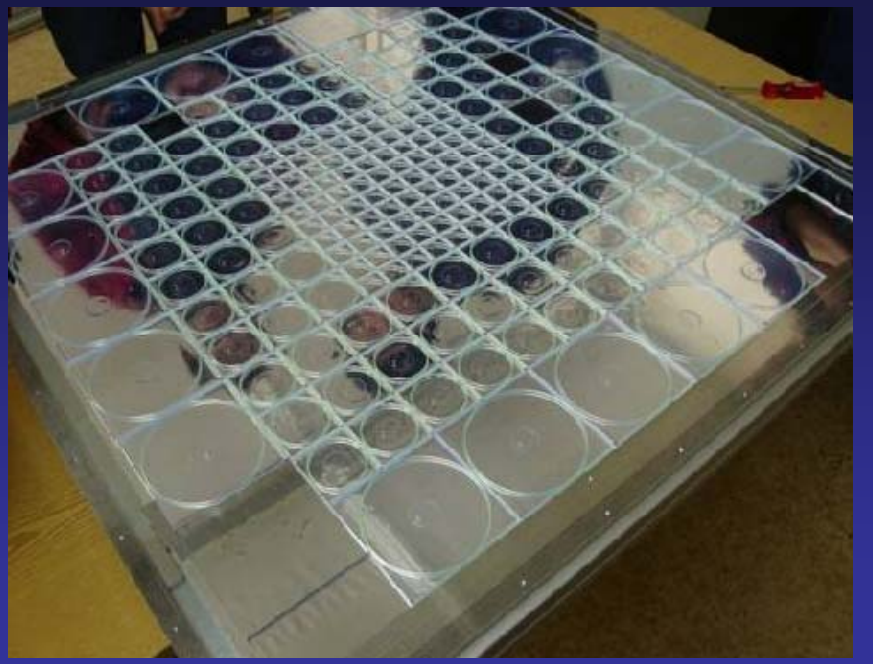


Results

Resolution as expected from simulation
Longitudinal shower shape: problems with layer #6?

Scintillator HCAL

First calorimeter to use SiPMs



Physics prototype

38 steel plates with a thickness of 1 X_0 each
Scintillator pads of 3 x 3 → 12 x 12 cm^2
→ ~8,000 readout channels

Electronic readout

Silicon Photomultipliers (SiPMs)
Digitization with VME-based system (off detector)

Tests at DESY/CERN in 2006

23/38 readout planes
Electrons 1 – 45 GeV
Pions 6 – 50 GeV

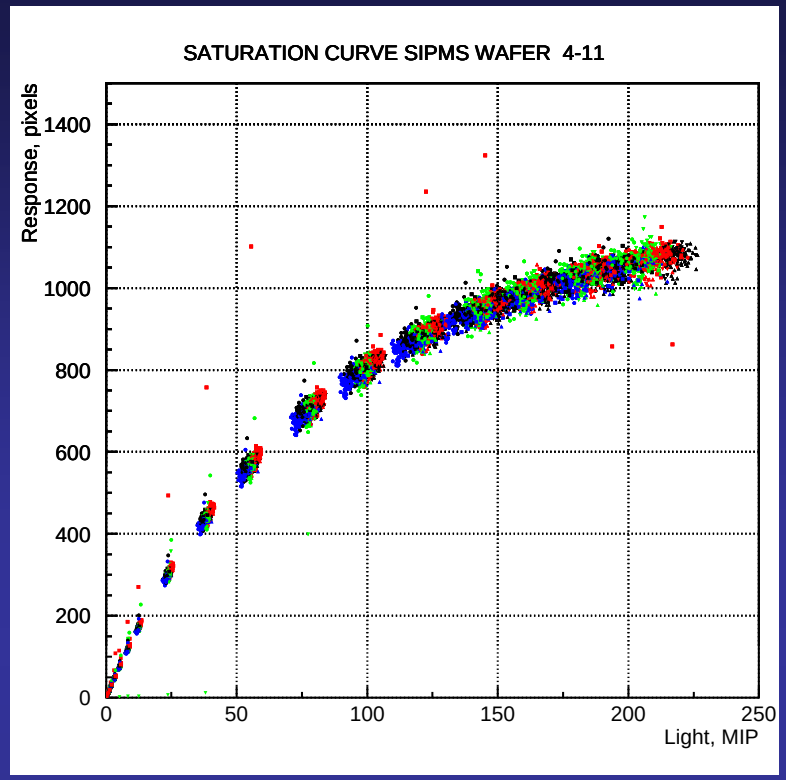
Calibration is important!

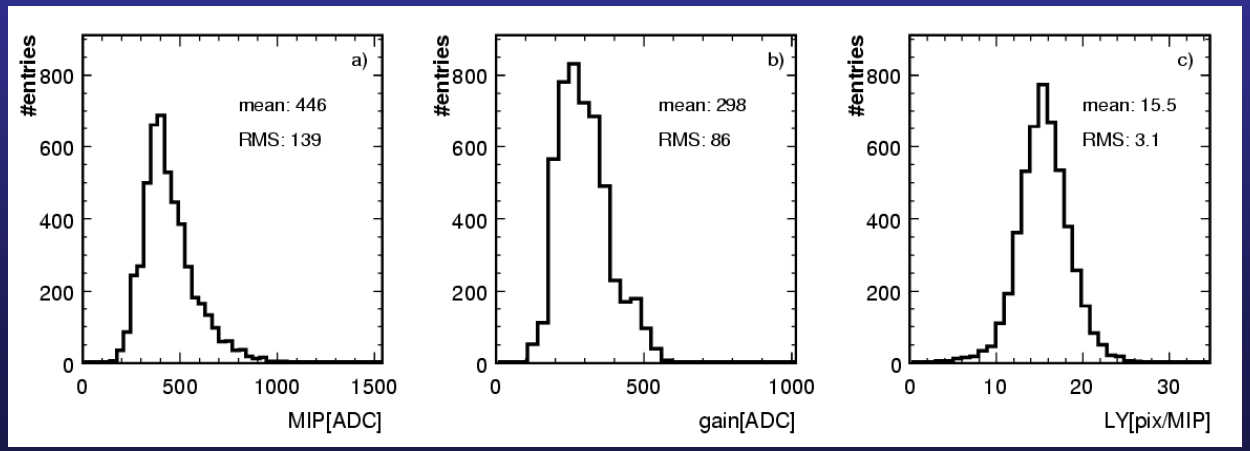
Corrections for

Light yield non-uniformity
SiPM gain variations (temperature, V_{bias})
SiPM non-linearity of response
Non-uniformity in readout electronics

$$A[MIP] = f_{resp}\left(A[ADC]\cdot\frac{I}{G}\right)\cdot\frac{G}{I\cdot M}$$

gain calibration **G** from low LED light:	$\sigma_G \approx 2\%$
⊕ intercalibration **I** from LED light:	$\sigma_I \approx 2\%$
⊕ non-linearity correction $\mathbf{f_{resp}}$ from ITEP curves:	$\sigma_f \approx 4\%$
→ Pixel uncertainty:	$\sigma_{pix} \approx 5\%$
⊕ MIP calibration **M** from muon beam:	$\sigma_M \approx 3\%$





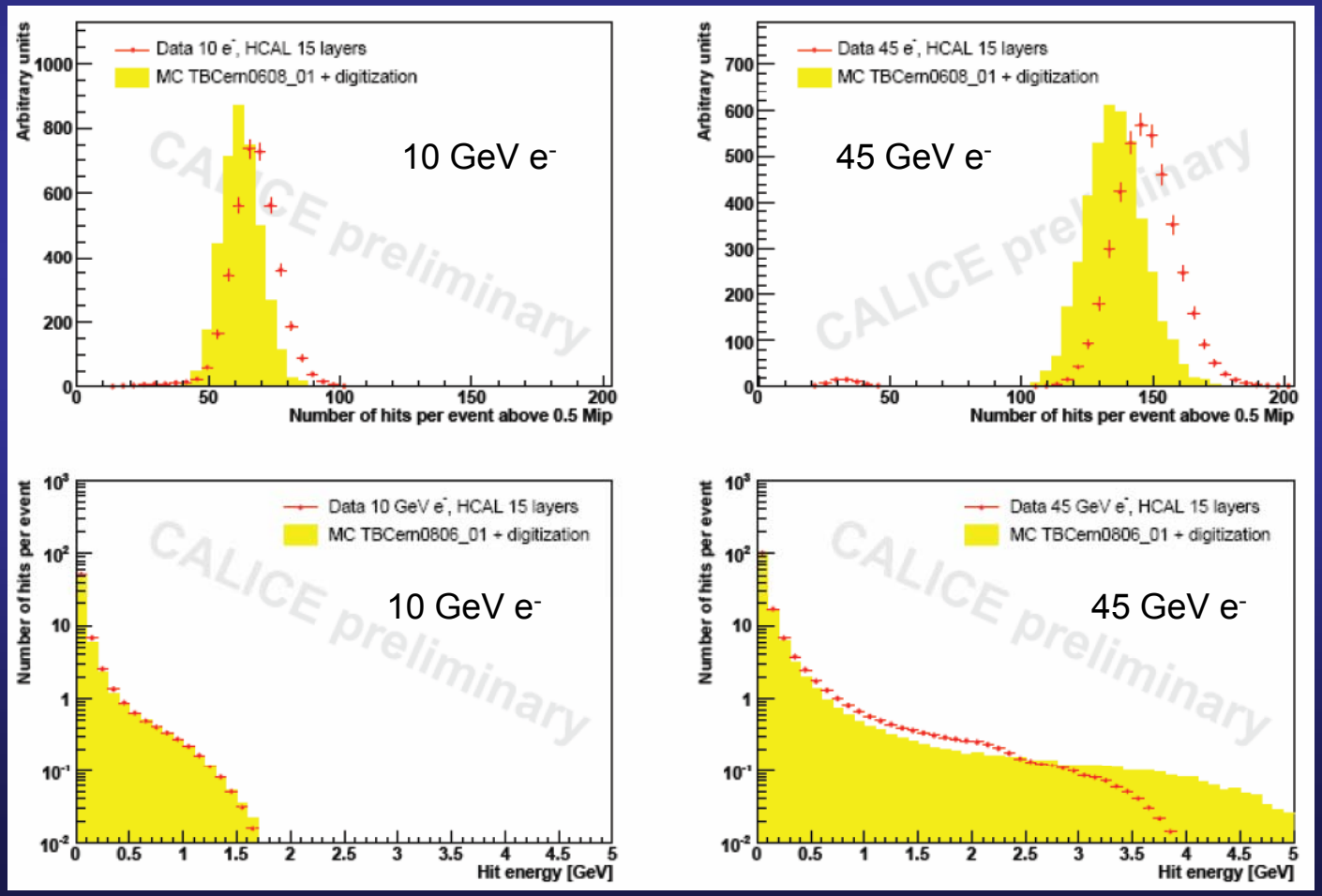
Light yield

Determined from ratio of MIP response and gain
Average ~16 pix/MIP
RMS ~ 20%

Analysis of electron data

Important cross check before tackling hadron data
More sensitive to SiPM non-linearity corrections

Number of hits and their energies

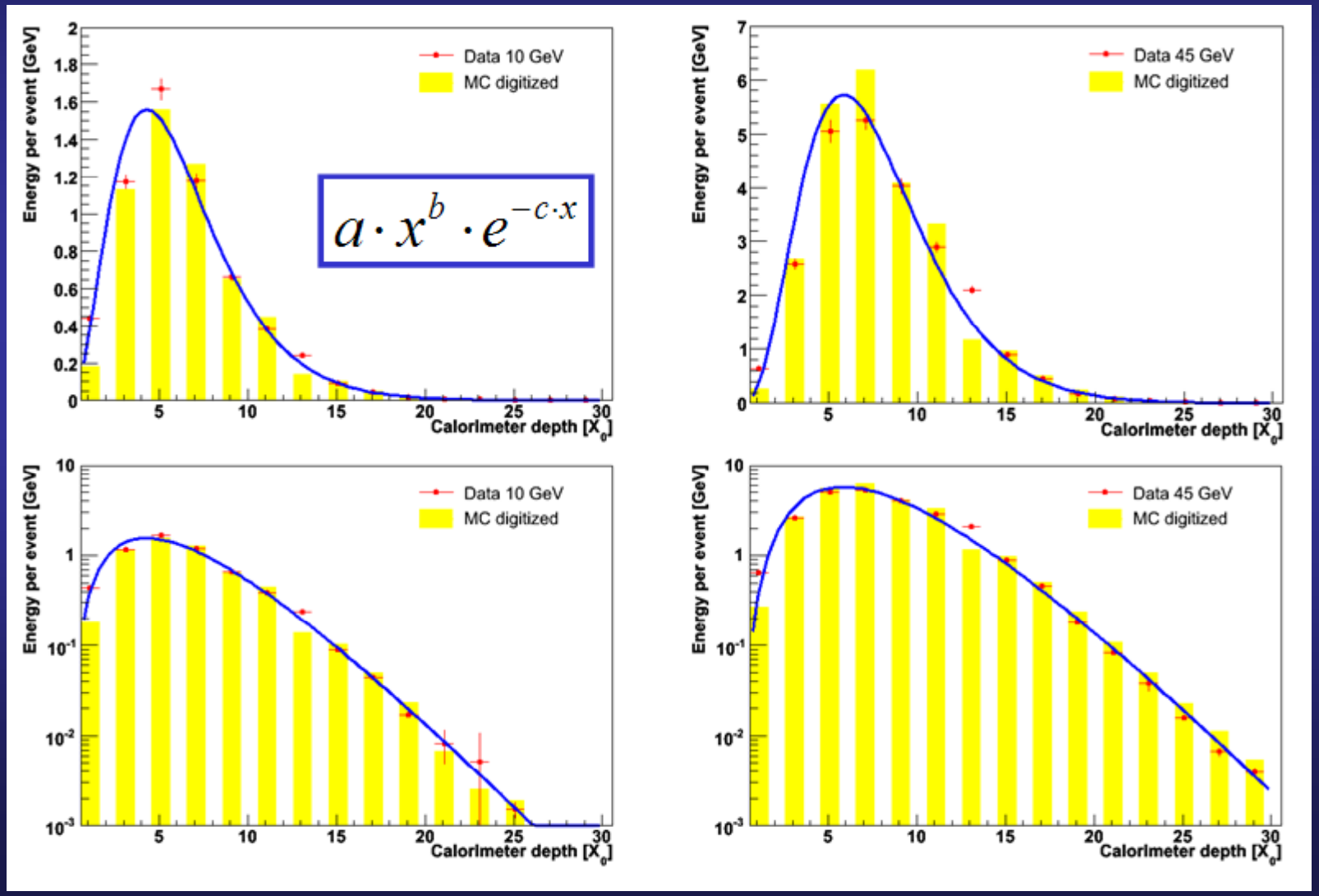


More hits in data than MC

Non-linearity corrections not yet perfect at high hit energies

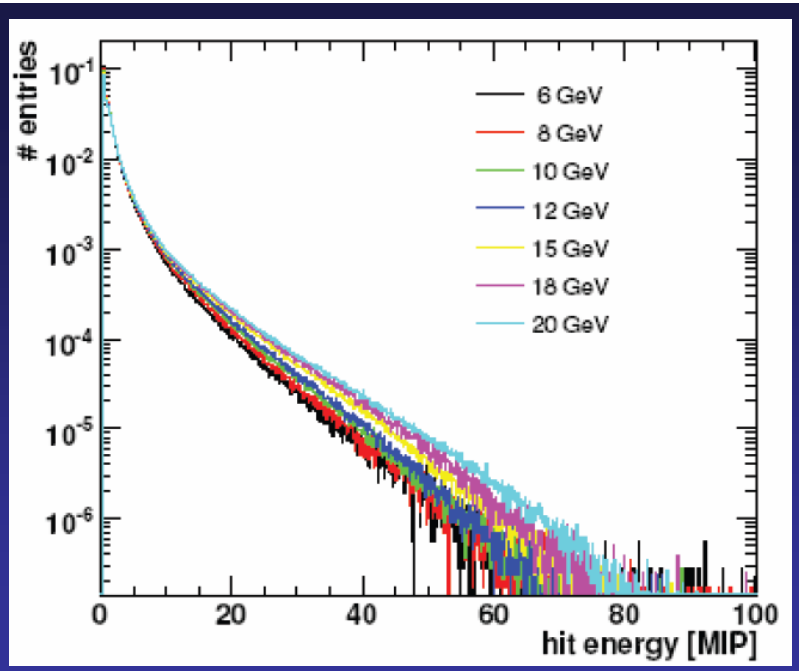
Electron data: Longitudinal shower profiles

Pretty good agreement with prediction
Shower maximum earlier in data: more dead material in beam line?



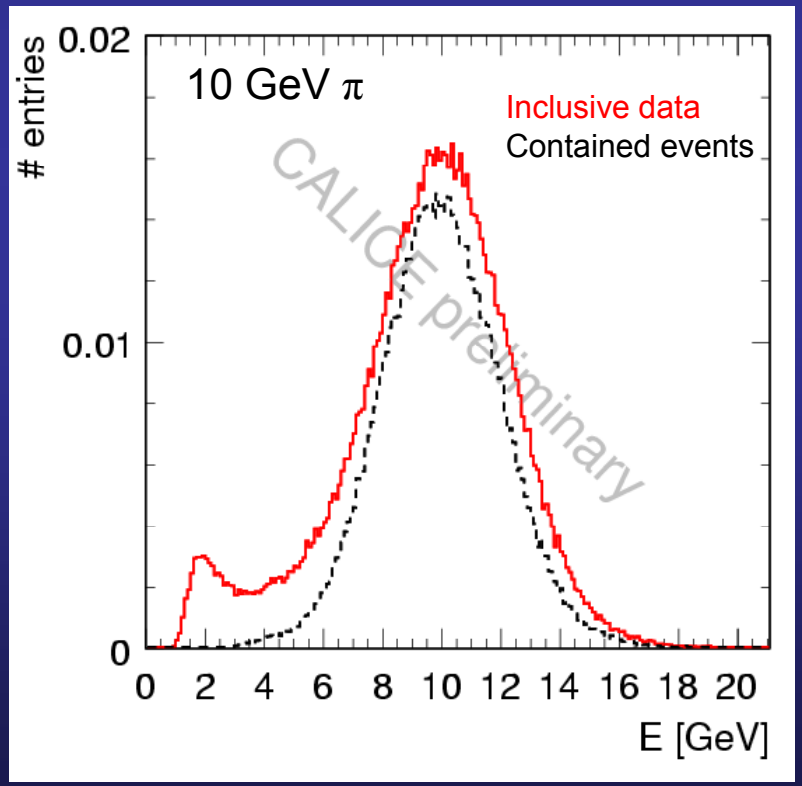
Analysis of pion data

Smaller hit energy
→ Less sensitive to SiPM non-linearity corrections



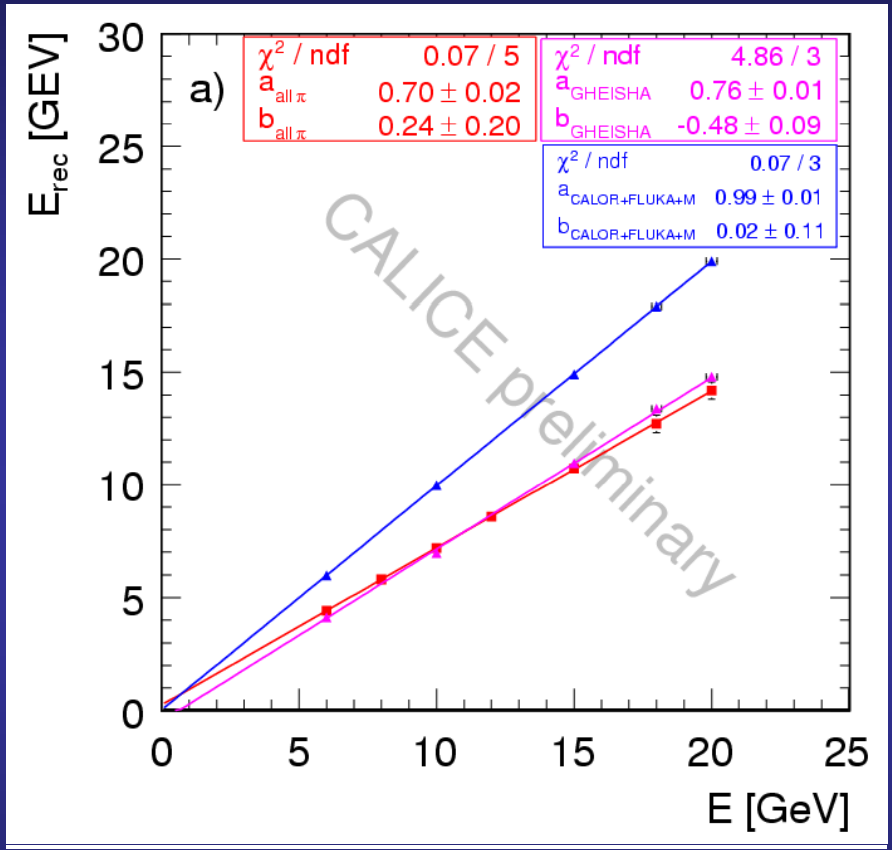
Analysis of inclusive and contained events

Use TCMT to reject events with leakage



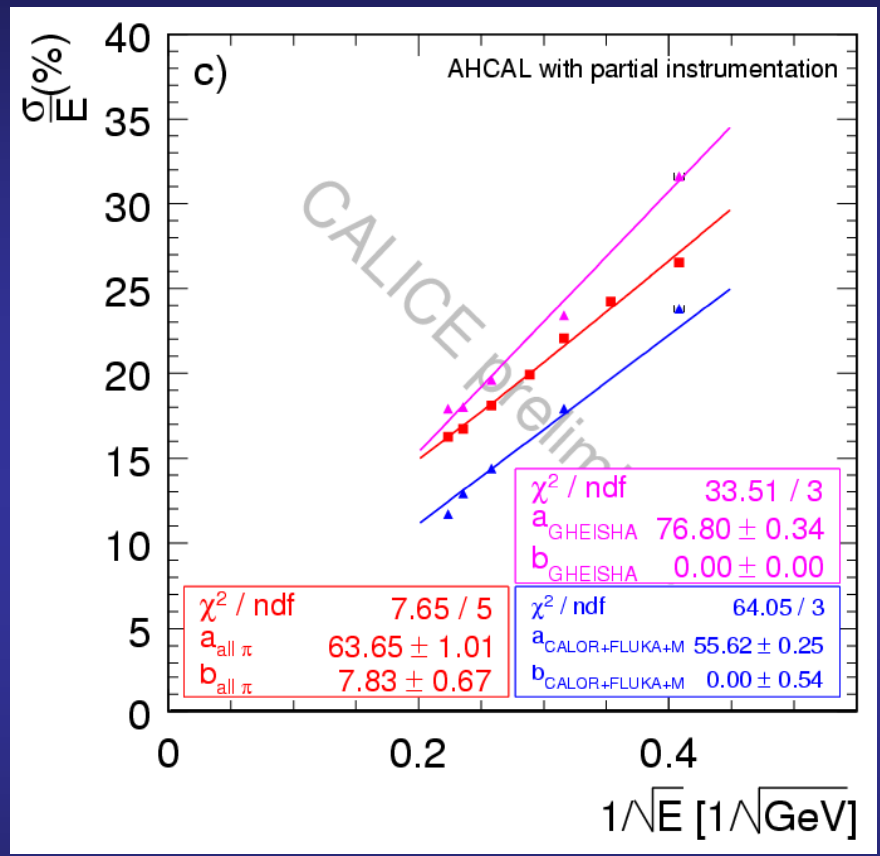
Response

Small residuals < 0.5%



Resolution

Fit contained data in the range ot ±1.5 σ

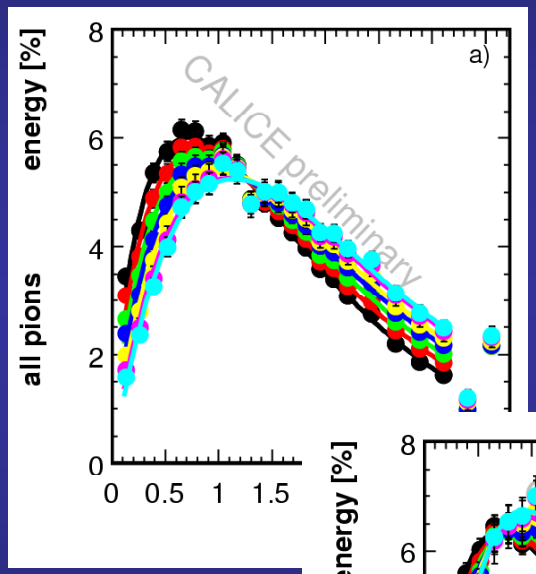


DATA

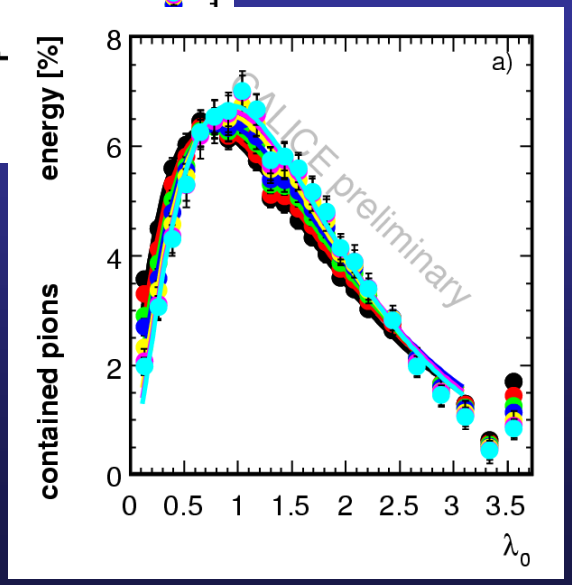
GCALOR+FLUKA+MICAP
GHEISHA
} Geant3

Shower Profiles

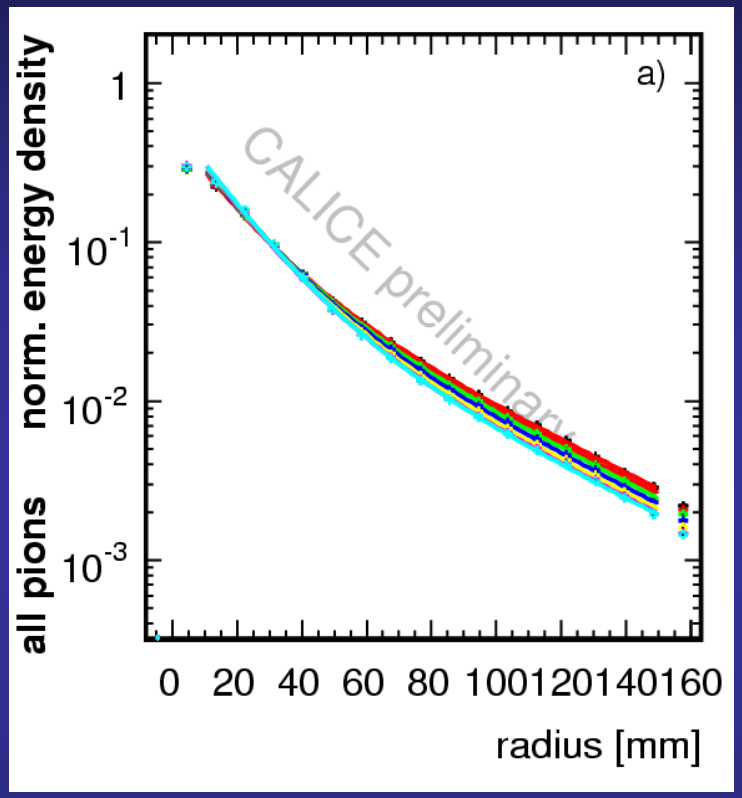
For different π energies between 6 and 20 GeV
Requirement of MIP signal in ECAL



Longitudinal shape



Transverse shape

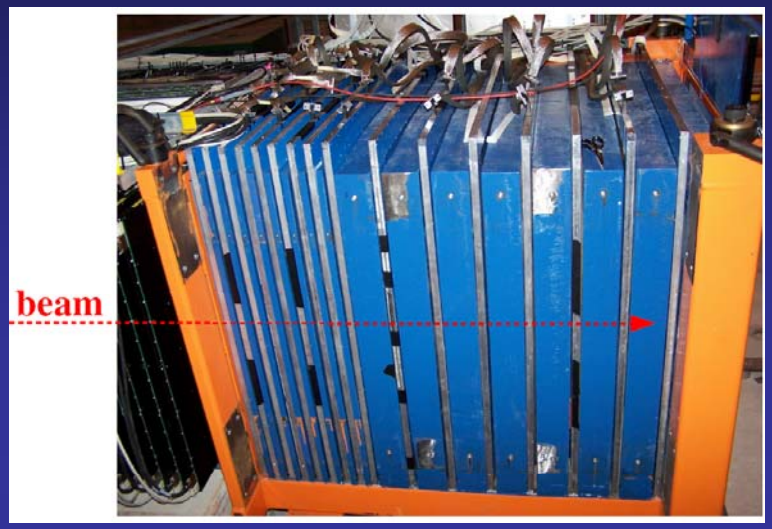


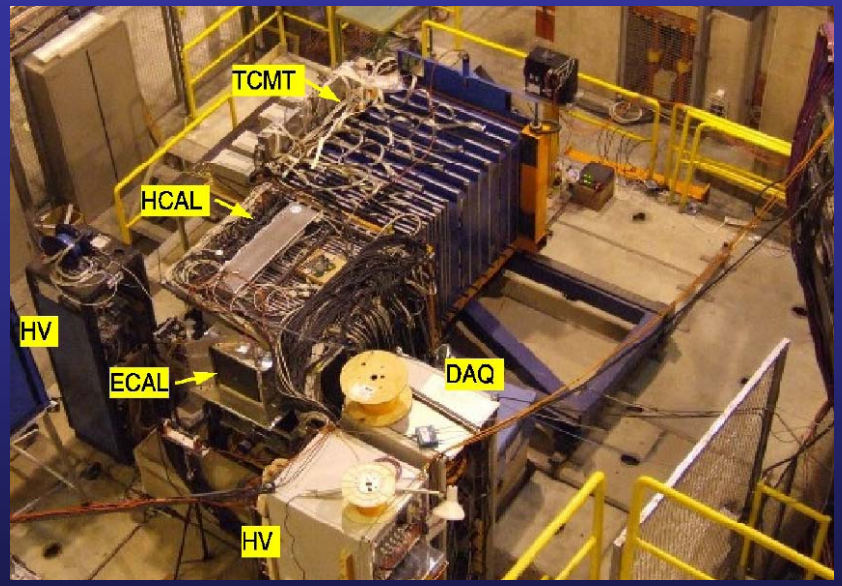
Comparison with simulation forthcoming…

Tail Catcher Muon Tracker (TCMT)

TCMT

Steel absorber: layers 1 – 8: t = 2 cm
9 – 16: t = 10 cm
Scintillator strips of 5 x 100 x 0.5 cm^3
Alternate x, y orientations
Complete TMCT in October 2006 CERN run





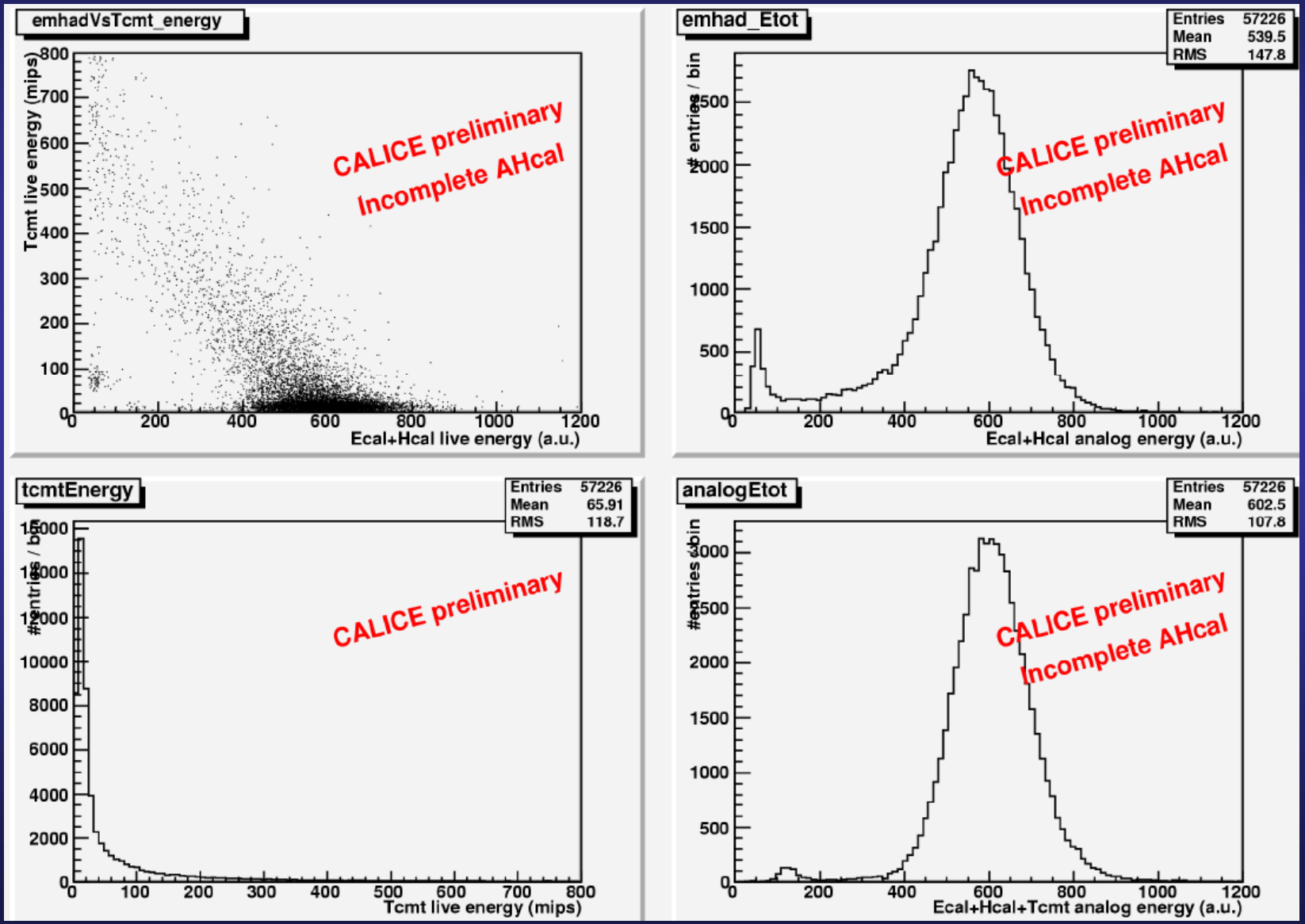
Electronic readout

SiPMs as for scintillator HCAL
Same electronic system as scintillator HCAL

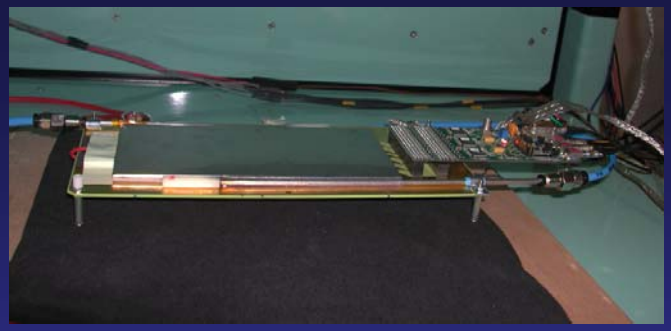
Combined analysis

Adding TCMT energies clearly improve resolution

20 GeV π



Digital HCAL



Active elements considered

Resistive Plate Chambers (RPCs): R&D (virtually) complete
Gas Electron Multipliers (GEMs): R&D ongoing
MicroMegas: R&D initiated

RPCs and GEMs were tested in FNAL test beam

Physics prototype

{16 mm steel plates + 4 mm copper (cooling) } x 38
Re-use stack from scintillator-HCAL

Electronic readout system

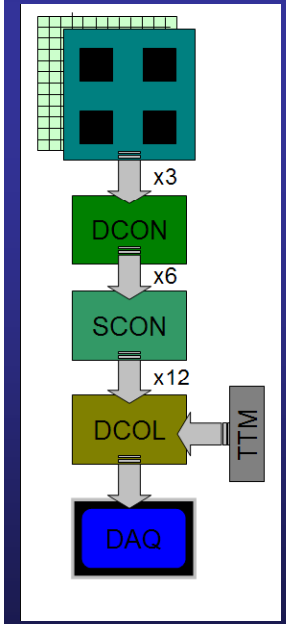
1 x 1 cm^2 pads with digital (single-bit) readout
→ Large number of channels (400,000 for physics prototype)
One-bit (digital) resolution with on-detector ASIC
Currently preparing Vertical Slice Test
→ if successful initiate construction of physics prototype

Vertical Slice Test

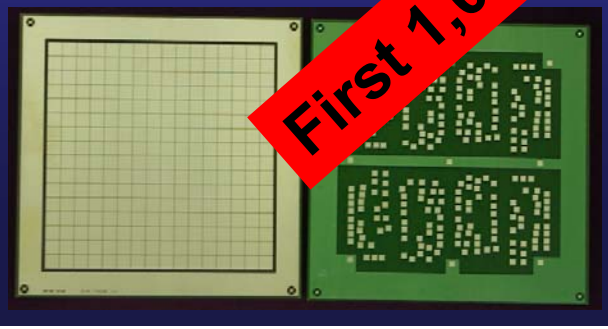
Involves 10 RPCs and 2 GEMs
~ Same electronic readout system as physics prototype section
Tests with cosmic rays and in FNAL test beam (June/July 2007)

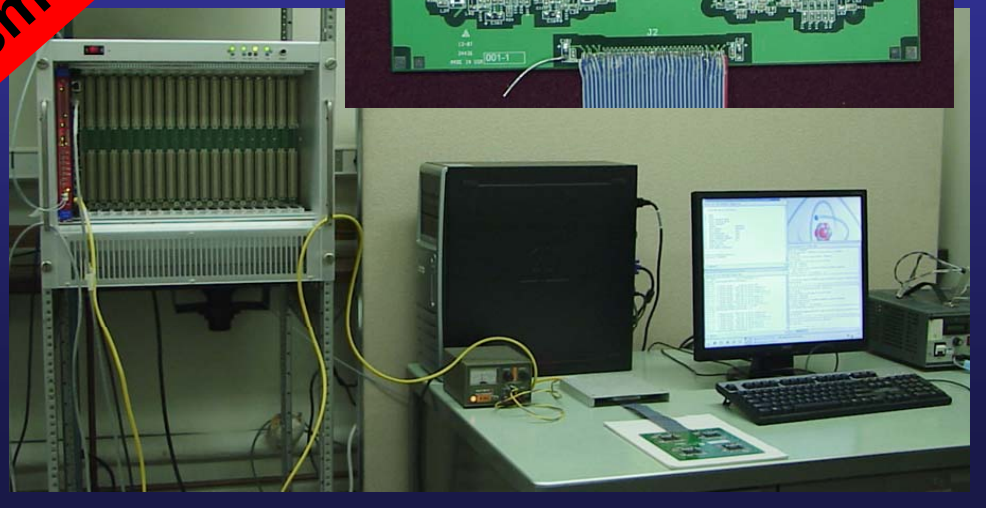
Current status

Cosmic ray test stand and test beam stack ready
RPCs and GEMs partially built and tested
Electronic readout system being commissioned



Front-end ASIC (DCAL chip) fully tested
Pad boards fabricated (no assembly)
Front-end boards: 2/12 assembled and tested
Data concentrators: 2/12 assembled and tested
Data collector: 3/1 assembled and tested
Timing and Trigger module: 1/1 being teste
DAQ software taking data
Offline analysis almost ready
Gas and HV systems ready
MoU with FNAL for test beam ed



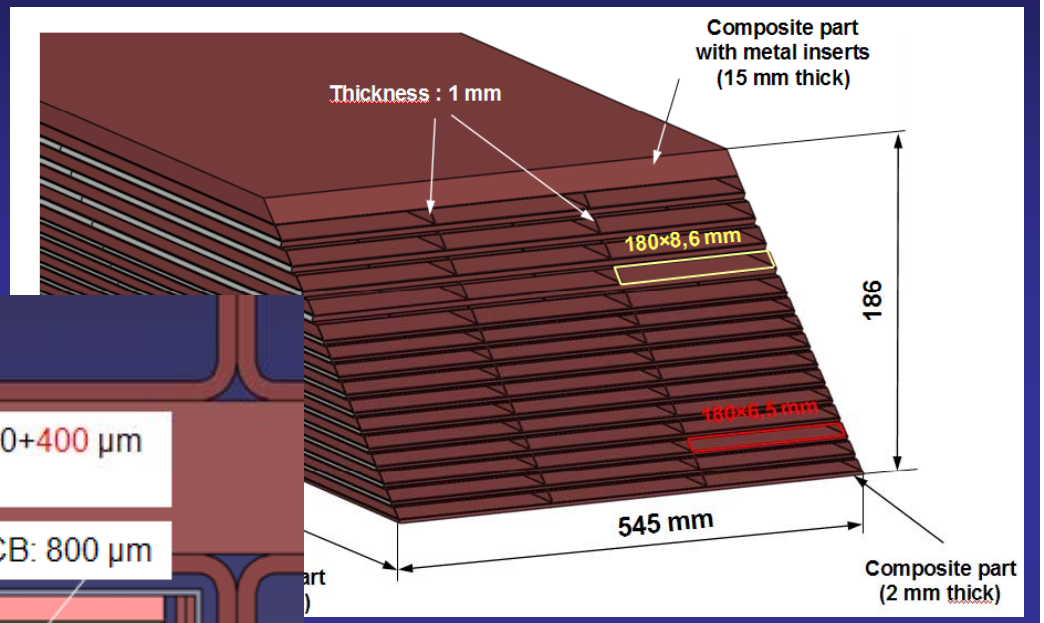


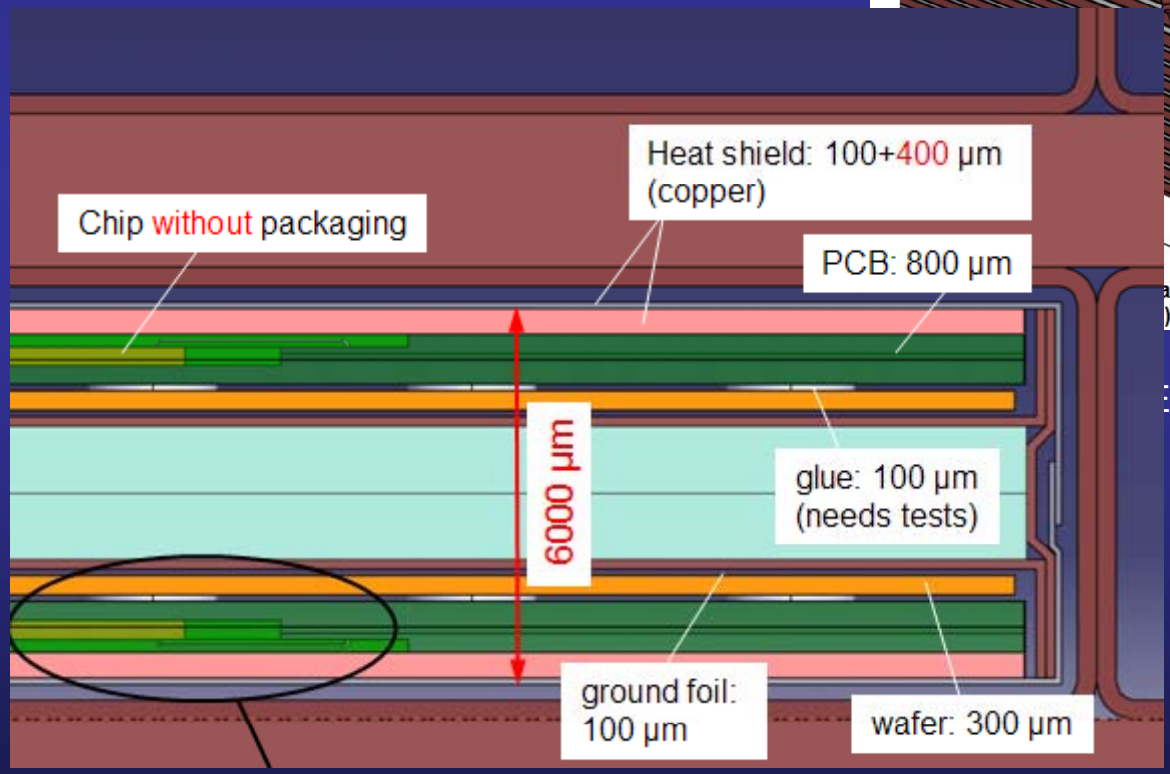
First 1,000 Cosmic Ray Events Collected

Towards Technical Prototypes

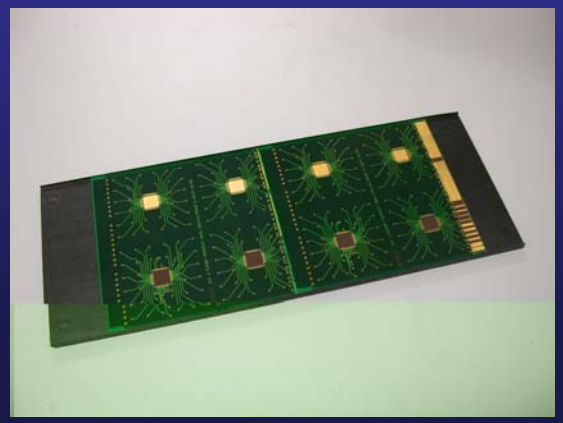
Silicon – Tungsten ECAL Module

Designing the alveolar structure
Many studies: cooling, gluing, production…





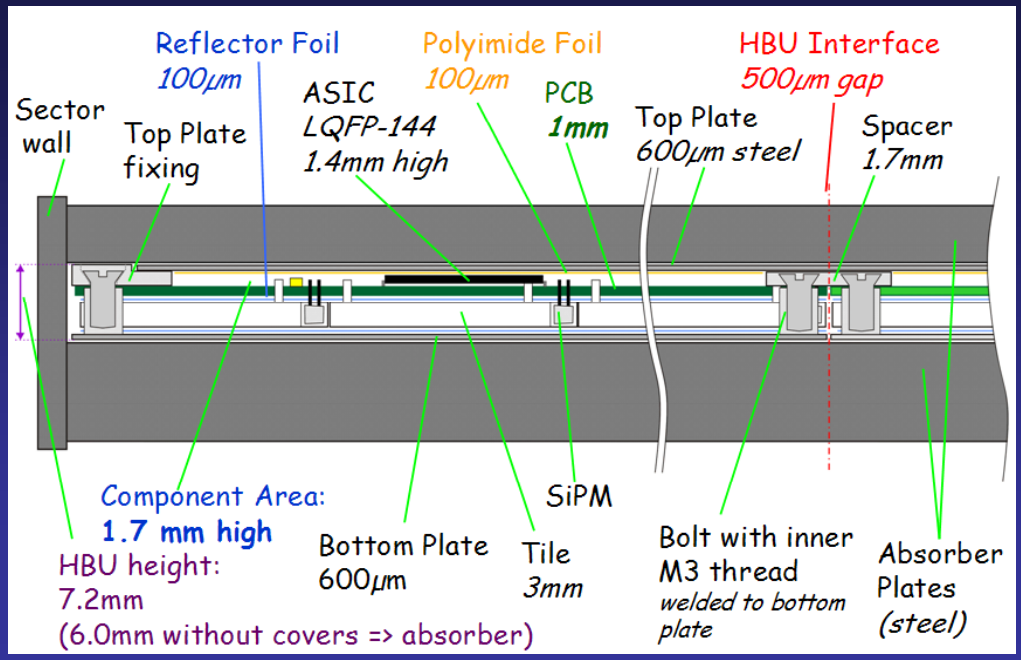
Effective active gap thickness ~ 2,200 µm



Chips and bonded wires
inside the PCB

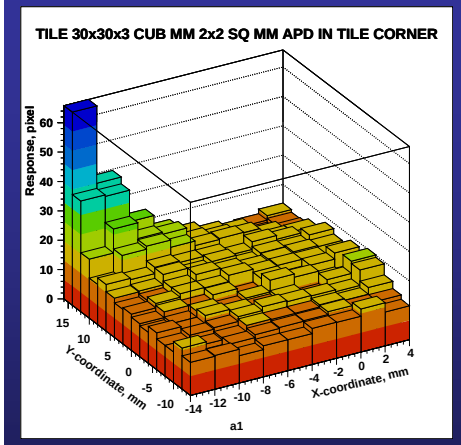
Scintillator – ECAL/HCAL

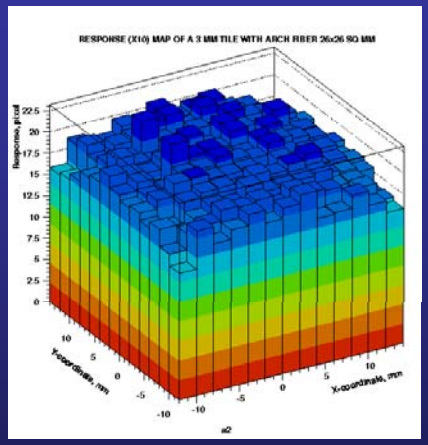
Designing HCAL base unit
Many studies: SiPM coupling…



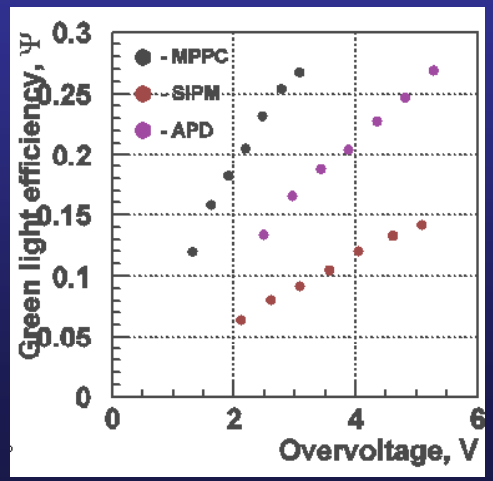
SiPM – MPPC Studies

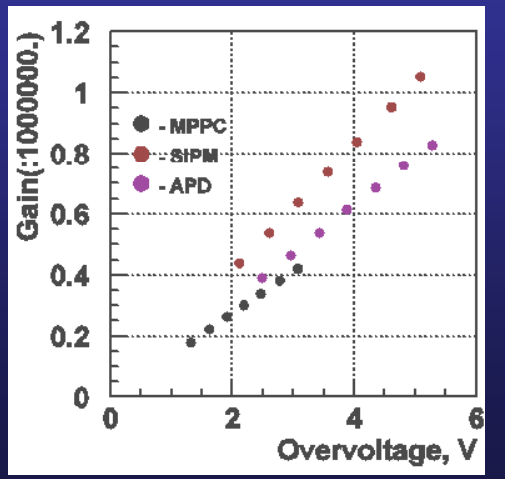
Uniformity across 3 x 3 cm² tiles for
direct or WLS readout





Comparison of SiPMs and MPPCs

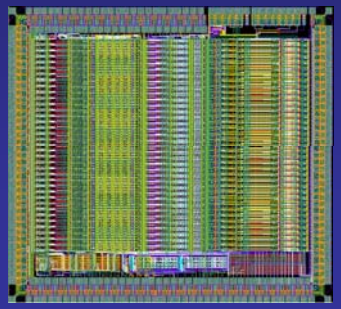




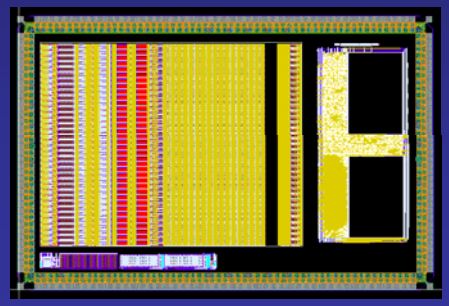
Very Front-end Electronics

Development of on-detector digitization ASICs
Power pulsing (reduction of power consumption)

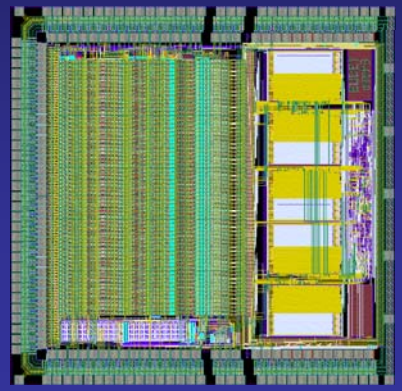
Si-W ECAL

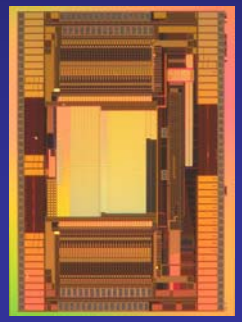


Scintillator E/HCAL

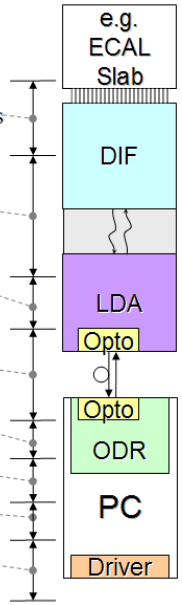


Digital HCAL





- **Detector Interface (DIF)**
  - Sub-detector specific, in conjunction with detector groups
- **DIF to LDA**
  - Generic, Copper links (25Mbit)
- **Link/Data Aggregator (LDA)**
  - Data format
  - Clock/Commands fan-out
- **LDA to ODR opto-links**
- **Off-Detector Receiver (ODR)**
- **ODR to disk**
  - PCI-Express driver software
- **Local Software DAQ**
- **Full blown Software DAQ**



2nd generation data acquisition

Development of new architecture

Using new tools, such as

High-speed networking
Optical switches
….

Conclusions

Test beam activities with physics prototypes

	Project	2007b	2008a	2008b	2009a	2009b
ECAL	**Si-W**	CERN test beam	FNAL test beam			
	MAPS	1st prototype chip		2nd prototype chip	DESY test beam	
	Scintillator			FNAL test beam		
HCAL	**Scintillator**	CERN test beam	FNAL test beam			
	RPC	Vertical slice test in FNAL test beam	Physics prototype construction	FNAL test beam		
	GEM	Vertical slice test In FNAL test beam	Further R&D on GEMs		Physics prototype construction	FNAL test beam
	MicroMegas		1 plane			
TCMT	**Scintllator**	CERN test beam	FNAL test beam			

+ further R&D, technical prototype designs, construction & testing…