The latest CALICE activities

Fabrizio Salvatore
Royal Holloway University of London

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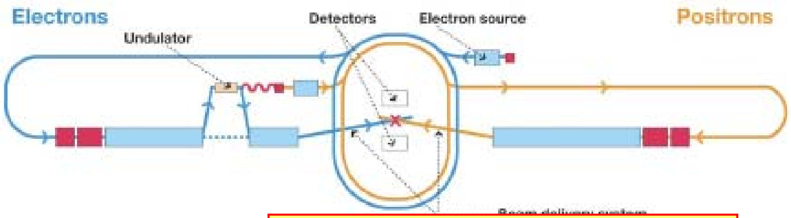
Rationale for a Linear Collider

- The LHC start up next year is expected to mark the beginning of a new era of exciting discoveries in particle physics
  - Higgs boson and TeV scale new physics (SUSY? ED?)
- However, despite its formidable potential as a discovery machine, the LHC will not be able to answer many questions about the nature of the new physics that is expected to be observed at the TeV scale
  - Proton-proton machine
- To do that, will need a machine where precision physics at TeV scale is possible
  - International Linear Collider (ILC)
    - Electron-positron machine
    - Clean and well controlled initial state



500 GeV – O(1TeV)

Challenges for detector design at ILC

Physics Process	Measured Quantity	Critical System	Critical Detector Characterstic	Required Performance
ZHH $HZ \to q\bar{q}b\bar{b}$ $ZH \to ZWW^*$ $\nu\bar{\nu}W^+W^-$	Triple Higgs Coupling Higgs Mass $B(H \to WW^*)$ $\sigma(e^+e^- \to \nu\bar{\nu}W^+W^-)$	Tracker and Calorimeter	Jet Energy Resolution, $\Delta E/E$	Jet Energy Resolution $\Delta E/E$ = 3-4%
$ZH \to \ell^+\ell^- X$ $\mu^+\mu^-(\gamma)$ $ZH + H\nu\nu \to \mu^+\mu^- X$	Higgs Recoil Mass Luminosity Weighted E_{cm} $B(H \to \mu^+\mu^-)$	Tracker	Charged Particle Momentum Res., $\Delta p_t/p_t^2$	Momentum Resolution $\Delta p/p^2 = 10^{-5}$ [GeV^{-1}]
$HZ, H \to b\bar{b}, c\bar{c}, gg$ $b\bar{b}$	Higgs Branching Fractions b quark charge asymmetry	Vertex Detector	Impact Parameter, δ_b	Impact Parameter Resolutio $\Delta\delta_b = 5 \oplus 10/p \sin^{3/2}\theta$ [μm]
SUSY, eg. $\tilde{\mu}$ decay	$\tilde{\mu}$ mass	Tracker, Calorimeter	Momentum Res., hermeticity	Solid Angle Coverage $\Delta\Omega = 4\pi - \varepsilon$

Excellent performances of all sub-detectors is a must !

Calorimetry at ILC

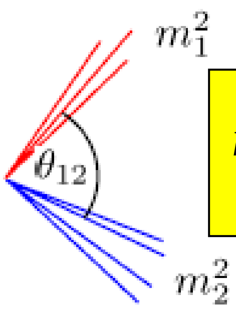
- Calorimetry is one of key ingredients for a high-specs detector at the ILC
  - Need high granularity for precise jet energy resolution
  - $\sigma_{jet} = \sigma_{charg} \oplus \sigma_{phot} \oplus \sigma_{neut} \oplus \sigma_{confusion}$
- Design, build and operate a novel detector which fulfils stringent requirements: $\sigma_{jet} / E_{jet} = 30\% / \sqrt{E}$

CALICE: build prototypes and perform an intensive test beam programme to characterize various calorimeter concepts

neutral hadrons	10 %	HCAL+ECAL	$\frac{\sigma_E}{E} \sim 45\%/\sqrt{E}$	$\sim 15\%/\sqrt{E_{jet}}$

Why 30%/√E ?

- Aiming at jet energy resolution giving di-jet mass resolution similar to Gauge boson widths



$$m^2 = m_1^2 + m_2^2 + 2E_1E_2(1-\beta_1\beta_2\cos\theta_{12}) \Rightarrow \frac{\sigma_m}{m} \approx \frac{\Gamma_{W/Z}}{m_{W/Z}} \approx 0.027$$

$$\frac{\sigma_{E_{jet}}}{E_{jet}} < 3.8\% \quad + \text{term due to } \theta_{12} \text{ uncertainty}$$

- Assuming $\sigma_E/E=\alpha(E)/\sqrt{E}$ (GeV)

⇒ $\sigma_m/m \approx \alpha(E_j)/\sqrt{E_{jj}}$ (GeV)

⇒ $\alpha(E_j) < 0.027\sqrt{E_{jj}}$ (GeV)

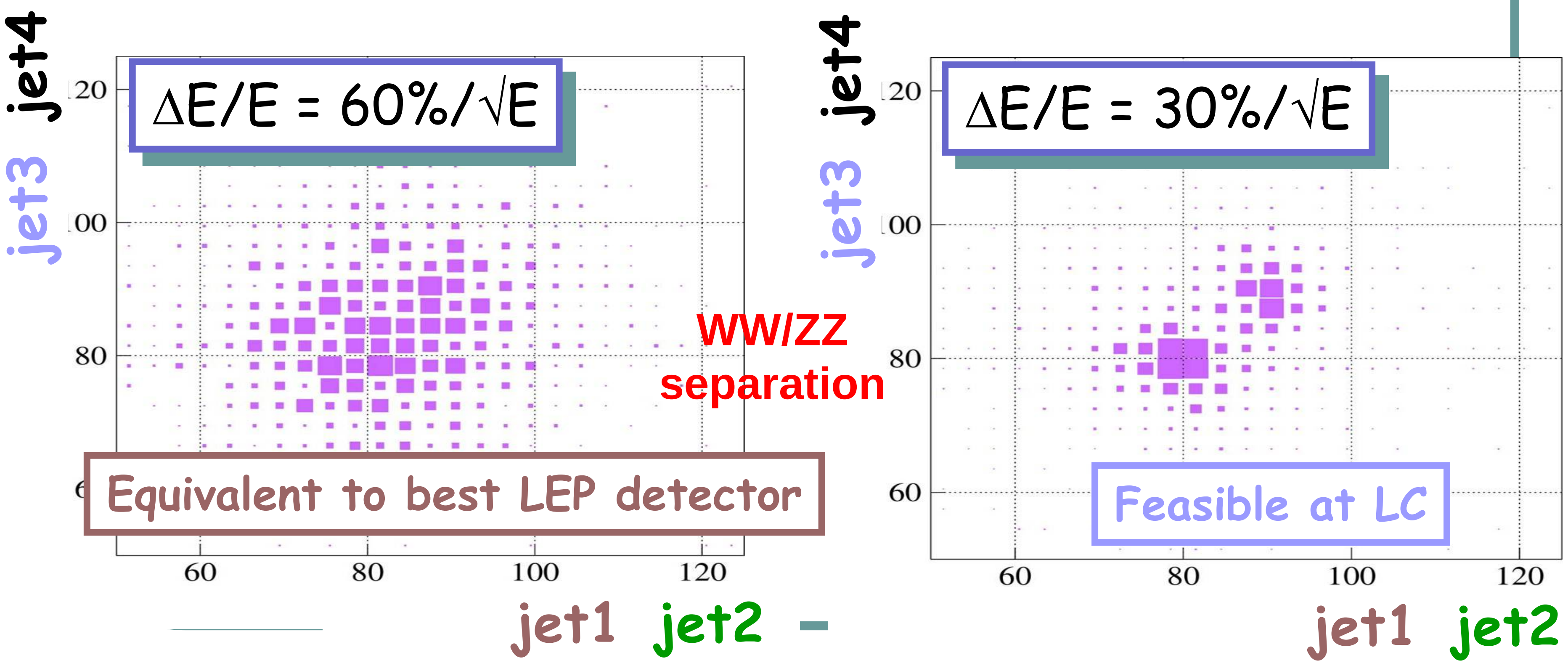
Tipical di-jet energies at ILC:

E_{jj}/GeV	$\alpha(E_{jj})$
100	< 27 %
200	< 38 %

$$\sigma_E / E = 0.30/\sqrt{E_{jj}(GeV)}$$

The Particle Flow paradigm

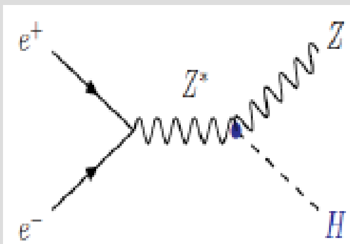
- Highly performing Particle Flow Algorithms (PFA) combined with high granularity calorimeters are a must to fulfil the ILC physics programme

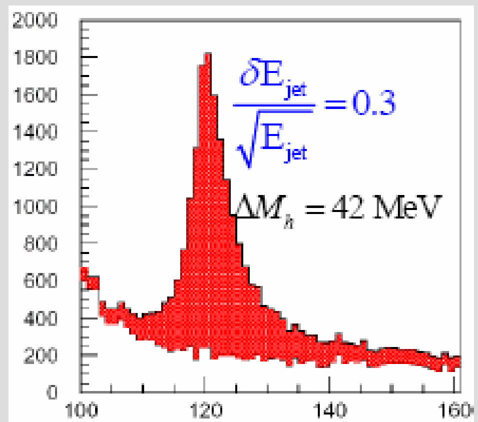


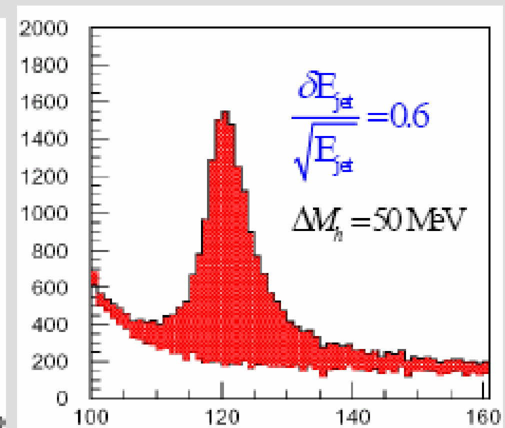
Challenges for Calorimetry

Good Jet Energy Resolution is worth 40% more integrated luminosity

- Improved Accuracy: Higgs mass from $e^+e^- \rightarrow ZH \rightarrow qqbb$

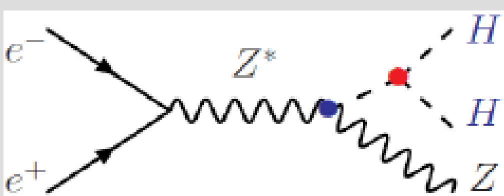




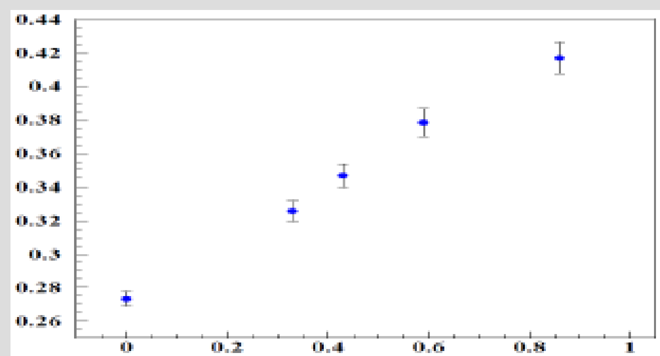


T. Barklow

- Significance for Higgs Self Coupling



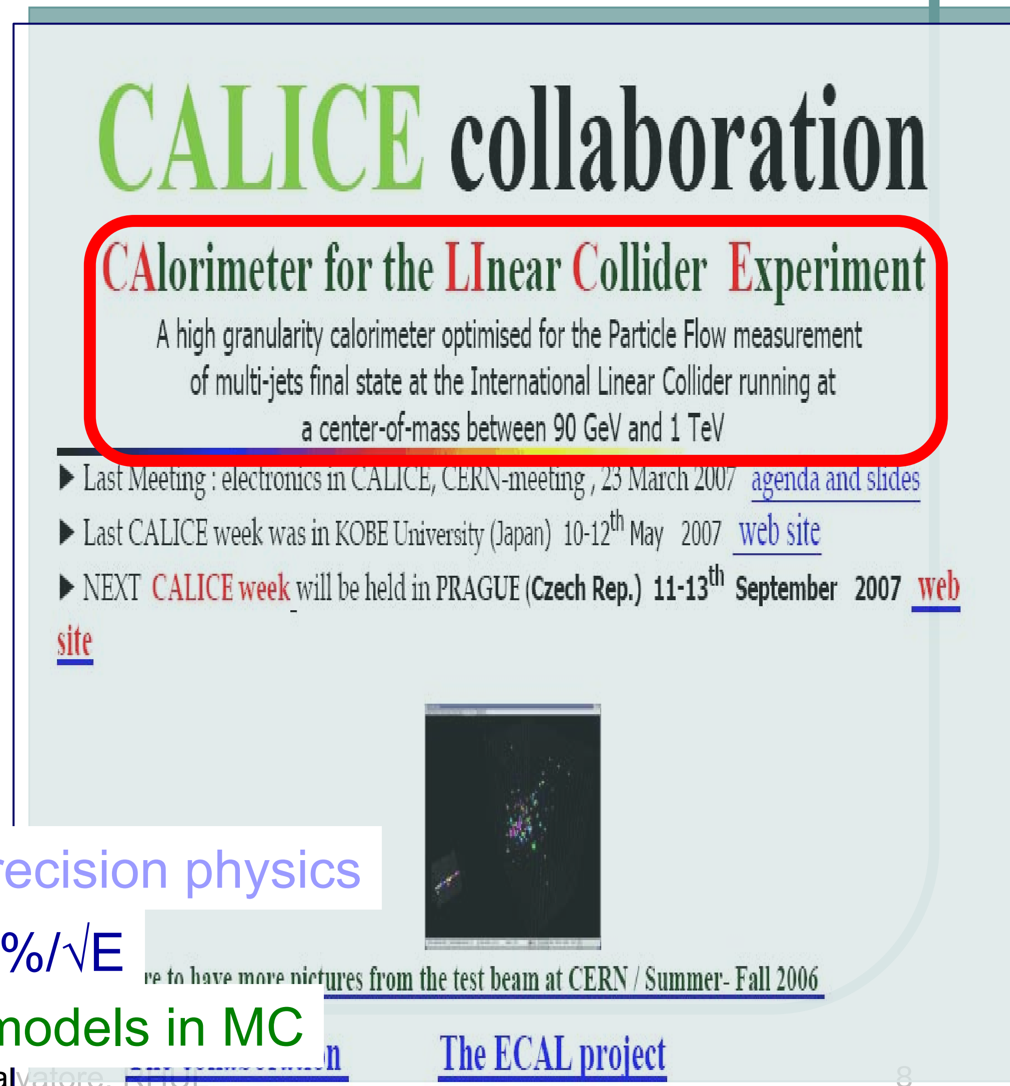
$$\frac{\Delta g_{hhh}}{g_{hhh}}$$



$\Delta E/\sqrt{E} \rightarrow$

The CALICE collaboration

12 countries,
45 laboratories,
225 physicists/engineers ,



- High granularity calorimeters for precision physics
- Study of particle flow for $\sigma_E/E \sim 30\%/\sqrt{E}$
- Validation of hadronic interaction models in MC

Goal of the collaboration

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

To measure electromagnetic and hadronic showers in high granularity detectors

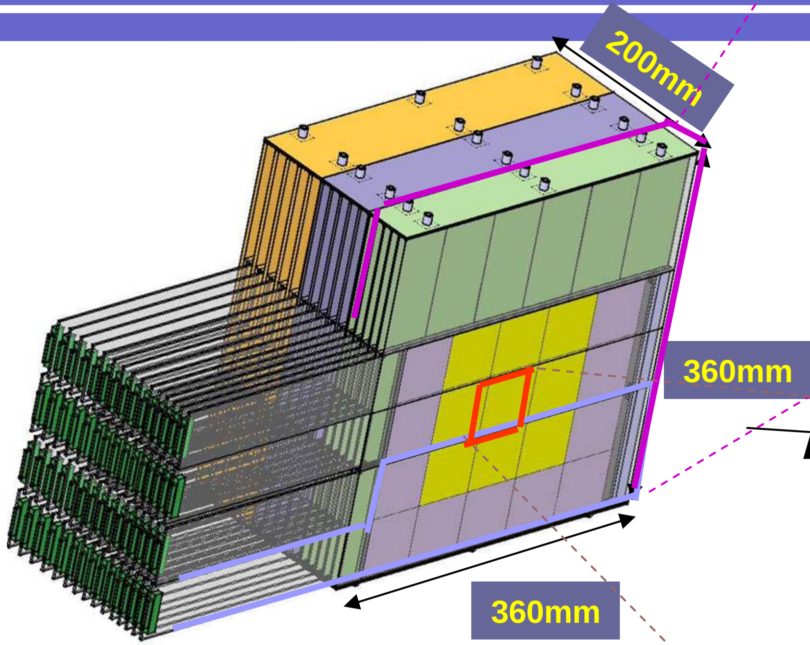
Characterization of physics/technical prototypes:

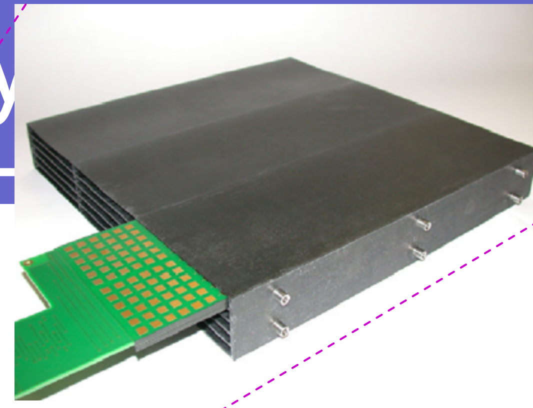
- Tests of different technologies (silicon, scintillator, gas)
- Definition of large prototypes ($1m^3$ for HCALs)
- Study of appropriate shapes for ILC detectors
- Study of mechanical issues (cooling, supports, etc…)
- Electronics and DAQ for prototypes and future ILC detectors
- Detailed test beam programs

To advance calorimeter technologies and our understanding of calorimetry

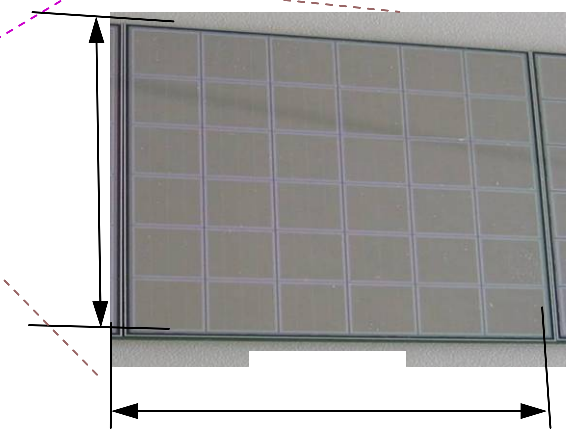
To design, build and test ILC Calorimeter prototypes

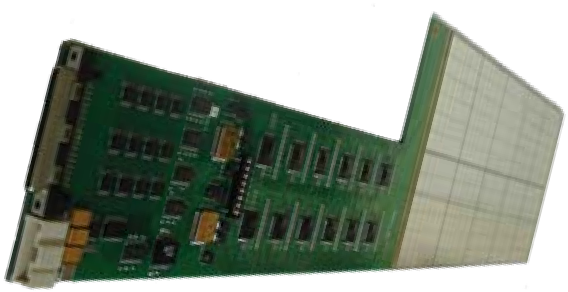
SiW ECAL prototy





- 6x6 1x1cm^2 Si pads
- Conductively glued to PCB





- W layers wrapped in carbon fibre
- 3 modules with different tungsten thickness, total = 24 X_0
- Active silicon layers interleaved: PCB+Si+W+Si+PCB layers = 8.5 mm
- FE chip and readout on PCB board

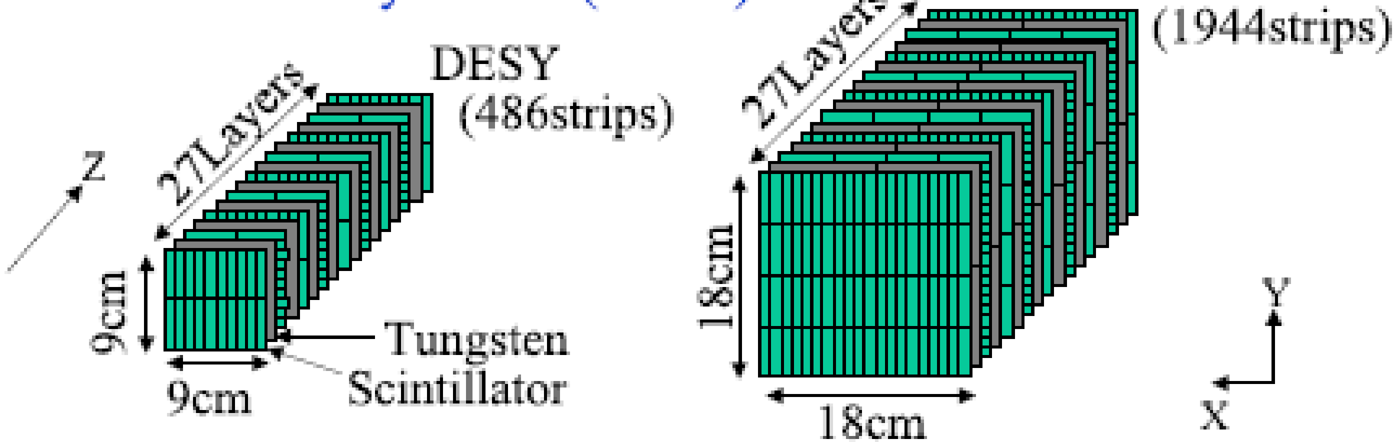
SciW ECAL prototype

Prototype ECAL - MPPC readout

Tungsten:3.5mm Sci. strip:3mm

Strip size: 1cm (width) x 4.5cm (length)

Number of layers: 27 (27 X_0)



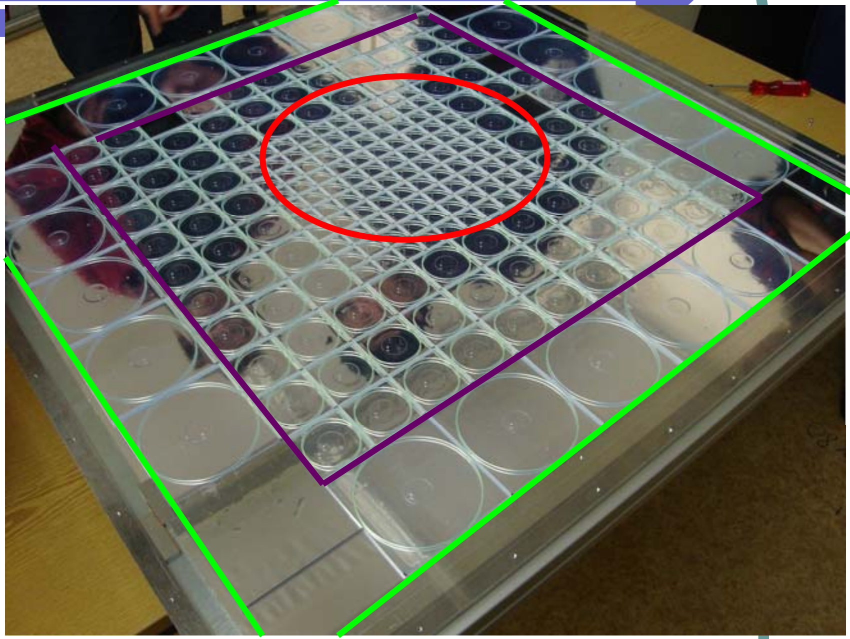
Cross section 9cmx9cm Test@DESY(This winter)

-> In EM shower (Non linearity of MPPC)

Cross section 18cmx18cm Test@Fermilab(2007)

-> In multi particle injection / Pi0 reconstruction

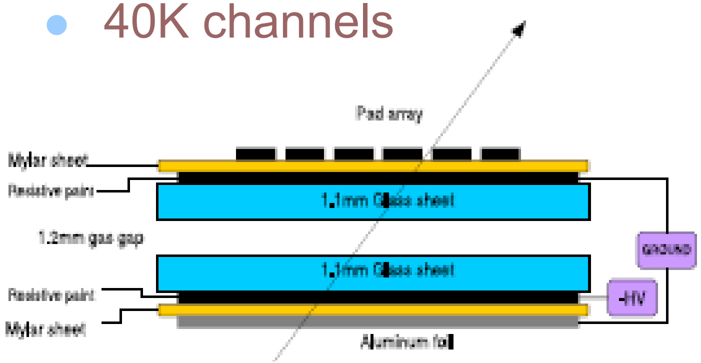
Analog HCAL prototype



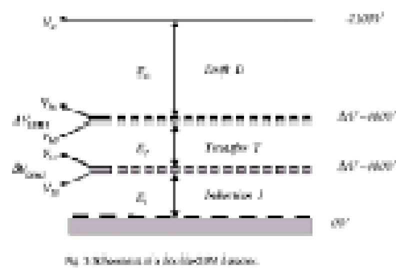
- 38 layers of scintillator tiles ($90x90\ cm^2$) with steel absorber (15 in 2006 tb)
- High granularity
  - 3x3 + 6x6 + 12x12 cm^2 tiles
  - 30 modules with fine granularity (216 tiles) and 8 with coarse granularity (141 tiles)
  - 7608 readout channels (SiPM)
  - Total interaction length = 4.5 λ
- Common DAQ for ECAL+AHCAL+TCMT
- Measurements of shower leakage and μ identification provided by Tail Catcher + Muon Tracker (TCMT)
  - 96 cm of iron absorber with 16 layers of $5*50mm^2$ scintillator strips ($\sim 10\ \lambda$)

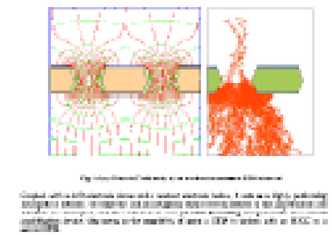
DHCAL prototypes

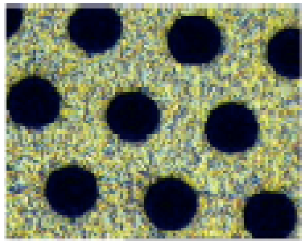
- RPC + steel absorber (1x1 cm^2)
  - 1m^3 prototype, 4.5 λ_I
  - 40K channels

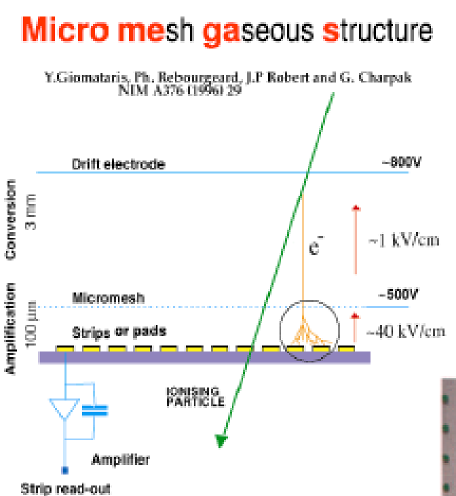


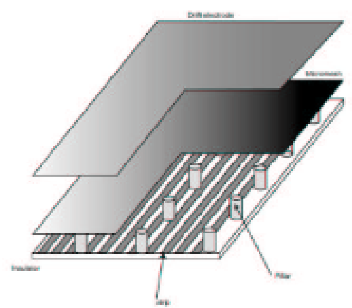
- GEMs + steel absorber (1x1 cm^2)
  - 1m^3 prototype, 4.5 λ_I
  - 40K channels

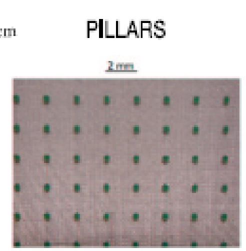


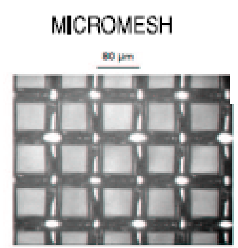






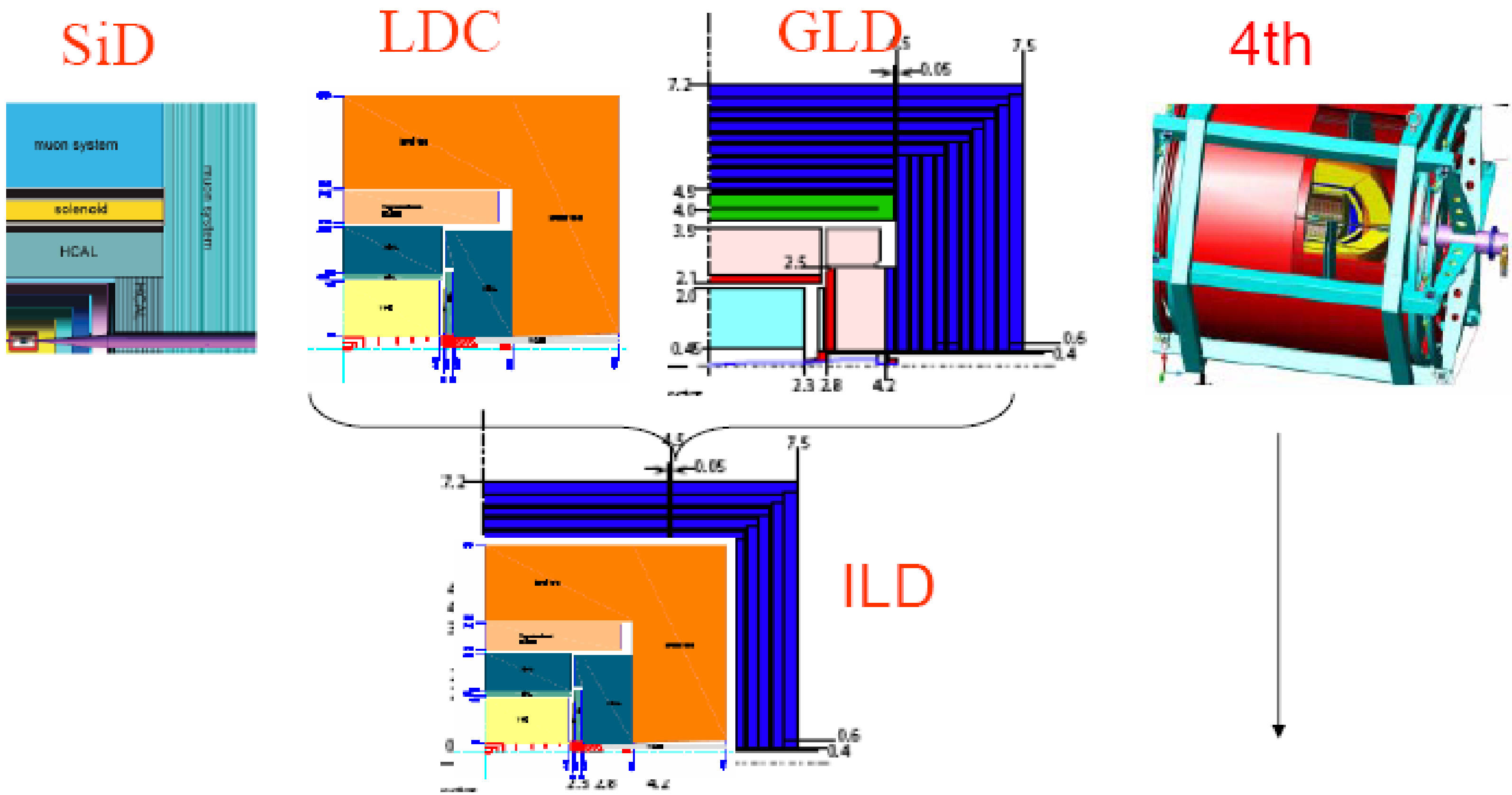






- Layers equipped with Micro MEsh GAseous Structure chambers
  - Readout by pads or strips

Evolution of the detector concepts



- Solenoid Designs B=5,4,3 Tesla
- Si vs TPC Tracking
- “Particle Flow” Calorimeters

- Dual Solenoid
- Compensating Cal
- TPC Tracking

Calorimeter models

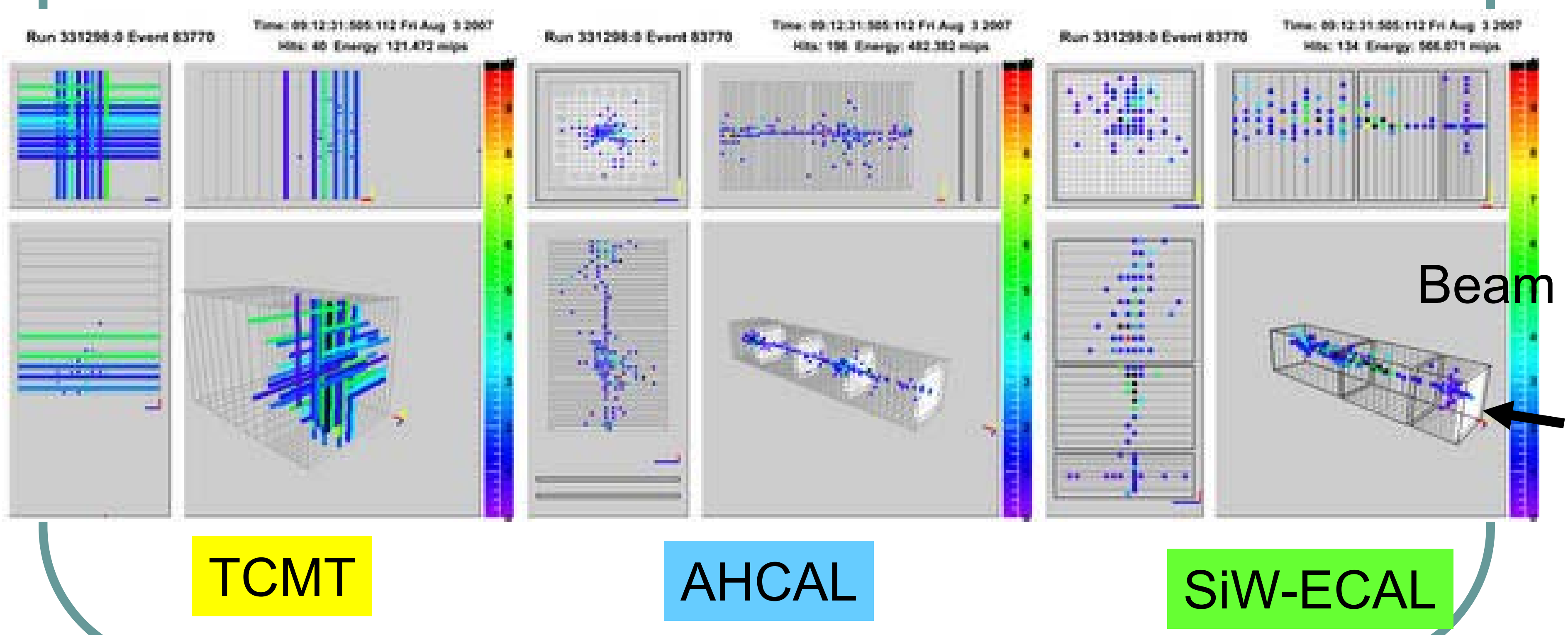
CALICE Projects	
ECALs	Silicon - Tungsten
	MAPS - Tungsten
	Scintillator - Lead / Tungsten
HCALs	Scintillator - Steel
	RPCs - Steel
	GEMs- Steel
	MicroMegas - Steel
TCMTs*	Scintillator - Steel

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

CALICE: very fine segmented detectors optimized for Particle Flow Algorithms

A real tracking calorimeter

We are working towards prototyping calorimeters for particle flow algorithms for the ILC !



Outline

- The 2006 CERN test beam
  - Data taking summary
  - Preliminary ECAL and AHCAL results
- The 2007 CERN test beam
  - Installation
  - Data taking overview
  - Detectors' performances
- Future test beam plans
- Other CALICE activities in the UK
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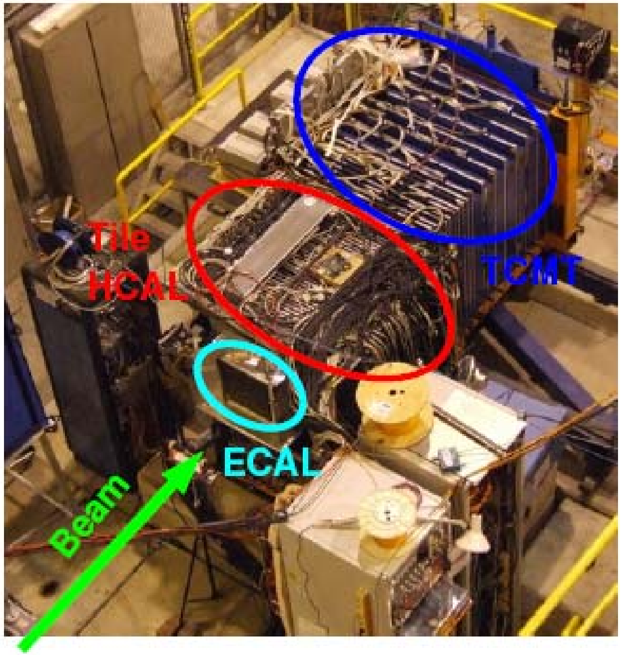
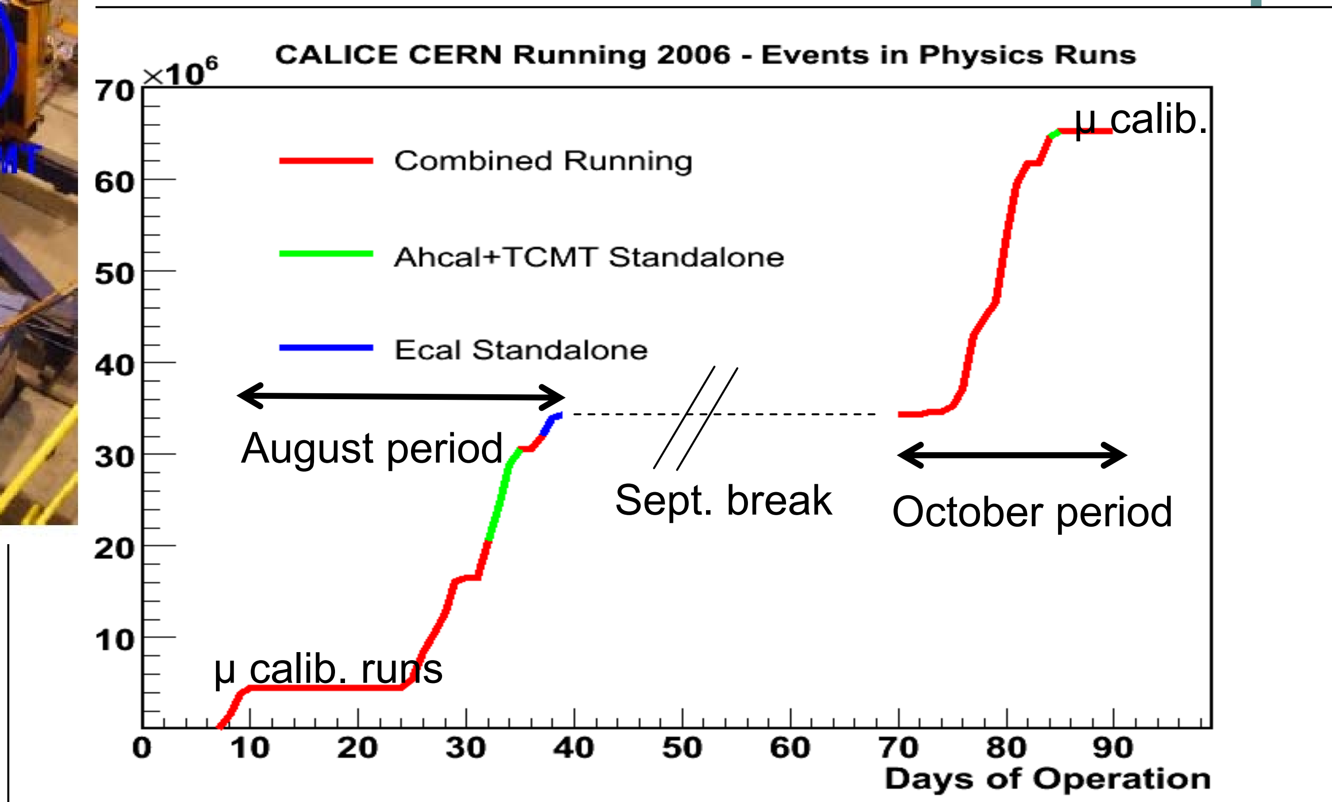
The 2006 CERN test beam

- Two beam periods
  - Aug 25th → Sept 6th
    - ECAL+AHCAL
      - 1.7M triggers
      - π beam
      - 5 E points (30-80 GeV), 3 angles
    - ECAL alone
      - 8.6M triggers
      - e⁻ beam
      - 6 E points (10-45 GeV), 4 angles
  - Oct 11th → Oct 30th
    - ECAL+AHCAL+TCMT
      - $e^{\pm}$ beams 3.8M trig., 10 E points (6-45) GeV
      - $\pi^{\pm}$ beams 2.2M trig., 11 E points (6-60) GeV
  - 70M muon events for calibration

Summary of the data taken



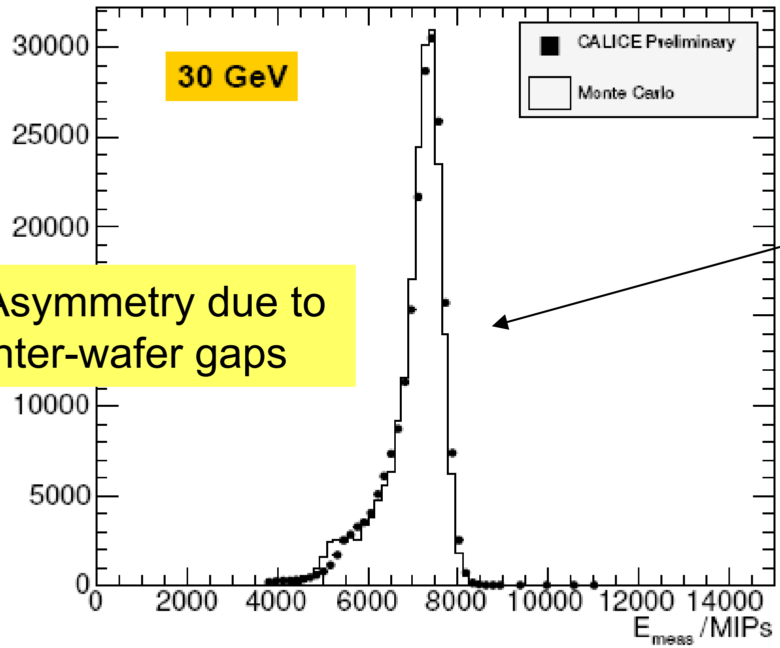


Size on disk: ~ 40 kB/evt

➔ 65M events = 2.5 TB for CERN Physics runs

➔ + 70 M = 3 TB for muon calibration runs

Preliminary results of ECAL analysis

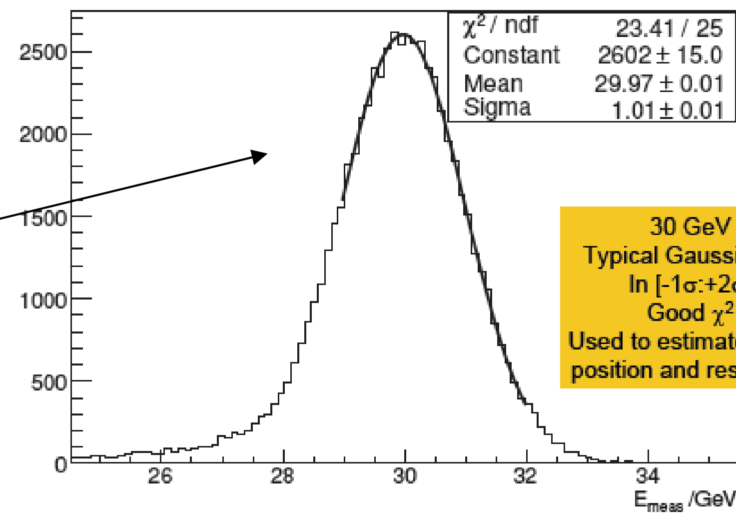


Asymmetry due to inter-wafer gaps

Raw energy spectrum

$E_{meas} = (\alpha_1 E(1\text{-}10) + \alpha_2 E(10\text{-}20) + \alpha_3 E(21\text{-}30)) / \beta$

$(\alpha_1, \alpha_2, \alpha_3) = (1, 2, 3) \quad \beta=250$

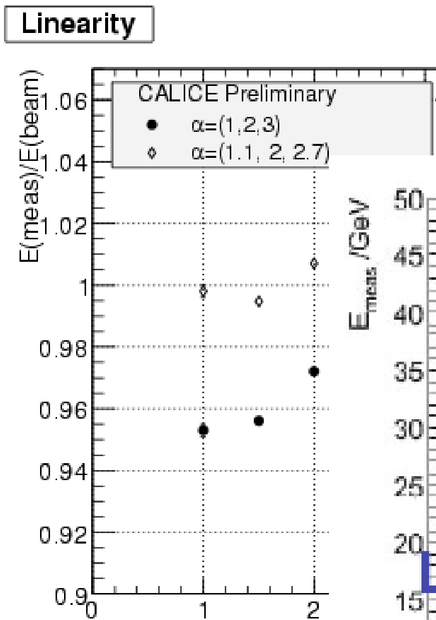


30 GeV
Typical Gaussian fit
In $[-1\sigma:+2\sigma]$
Good χ^2
Used to estimate peak position and resolution

Spectrum after selecting events outside gaps

Optimised weights for resolution: $(\alpha_1, \alpha_2, \alpha_3) = (1.1, 2, 2.7)$

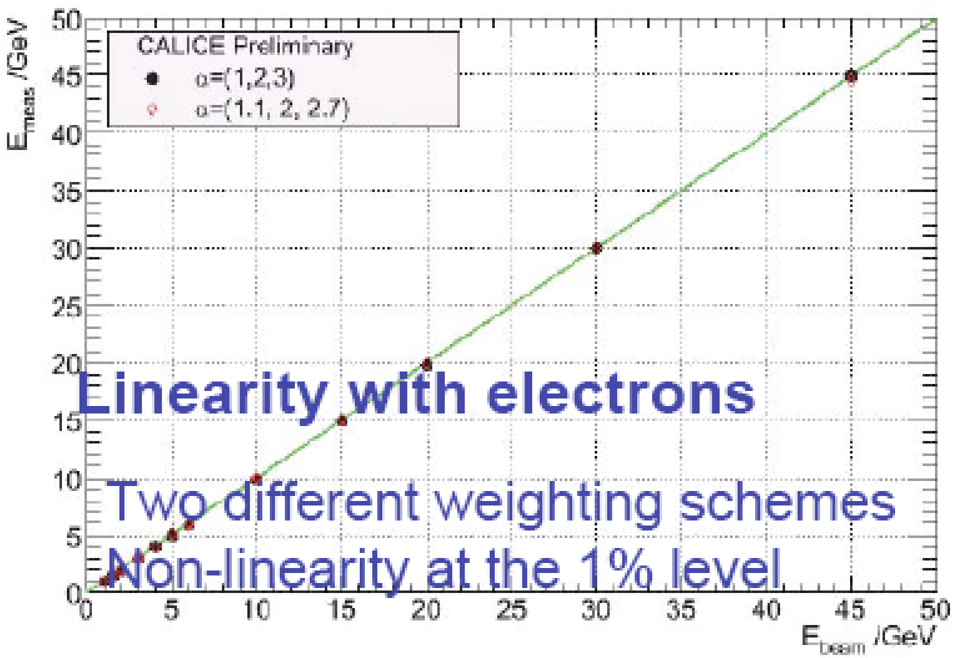
ECAL resolution and linearity



Desy

($\alpha_1, \alpha_2, \alpha_3$) = (1, 2, 3)

es at few % level

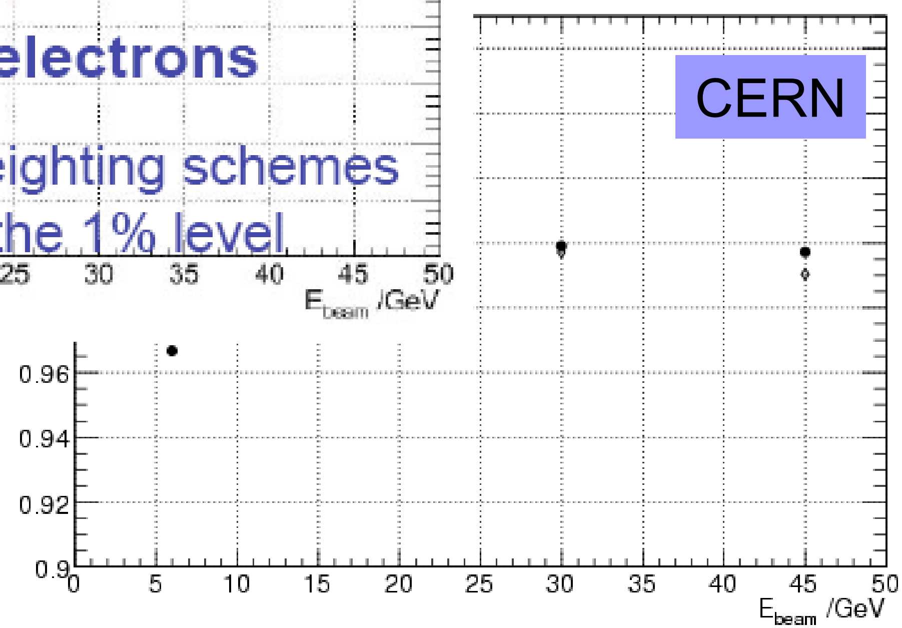


Linearity with electrons

Two different weighting schemes

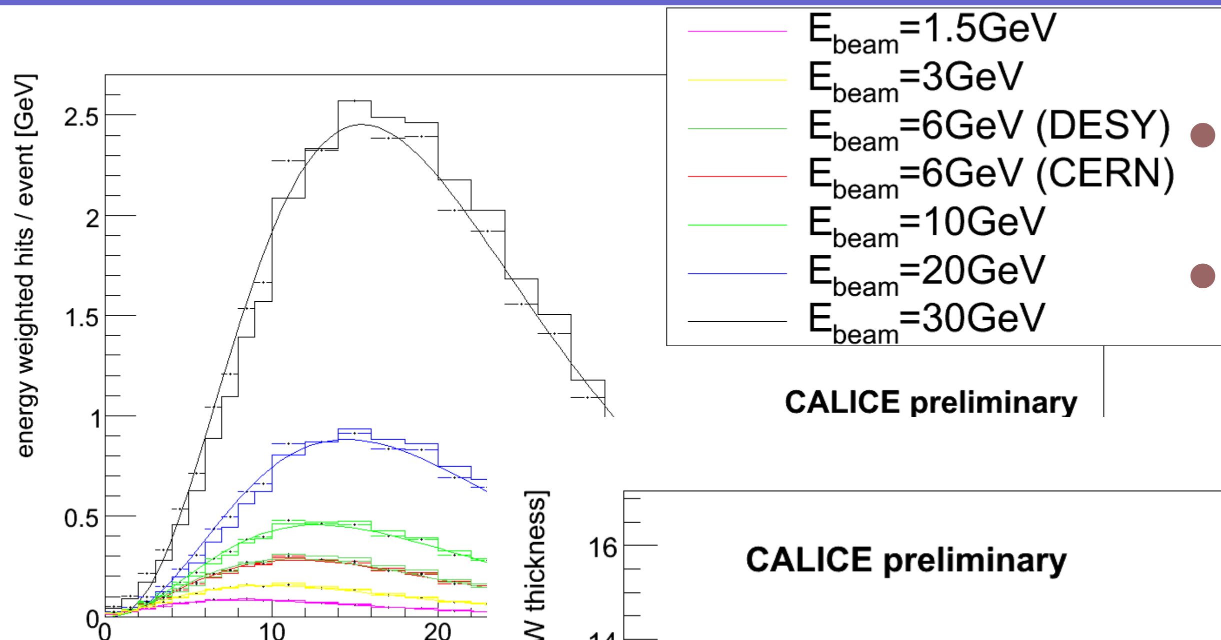
Non-linearity at the 1% level

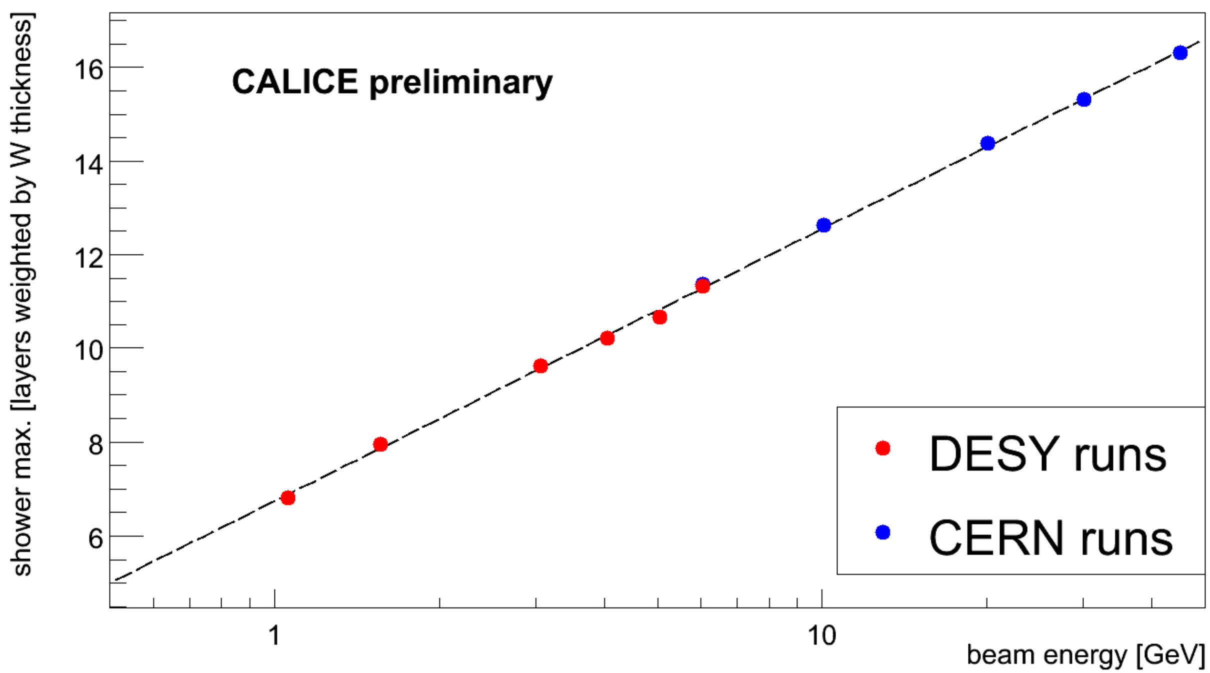
CERN



$$\frac{\Delta E}{E}(\%) = \frac{17.1 \pm 0.07}{\sqrt{E\,(GeV)}} \oplus (0.5 \pm$$

Longitudinal shower development

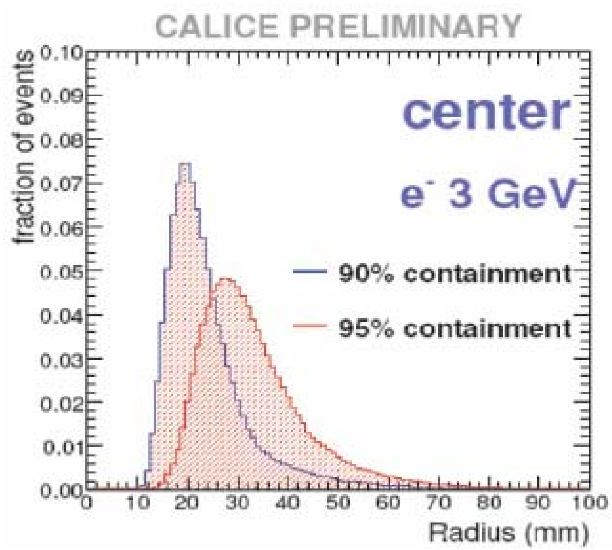


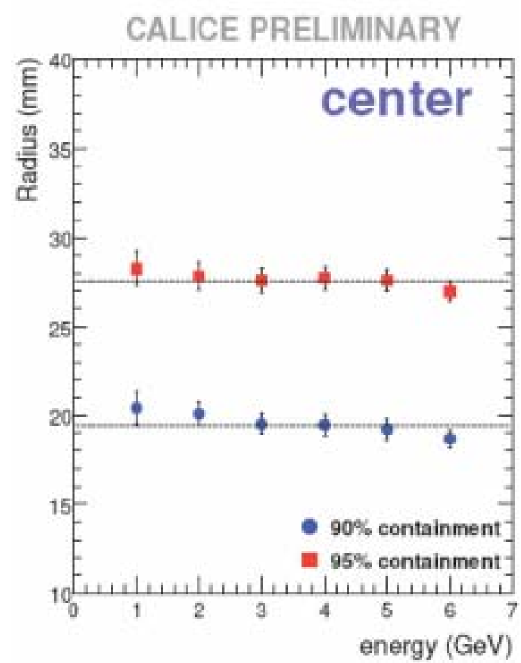


- More pre-showering in data than in MC
- Detailed analysis in progress:
  - Presence of inter-

Transverse shower profile

- 90% of EM shower contained in R_M
  - $R_M(W)$ = 9mm

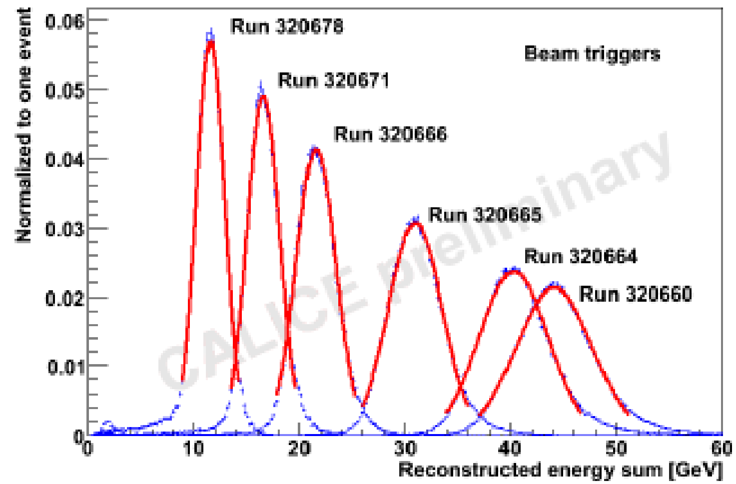


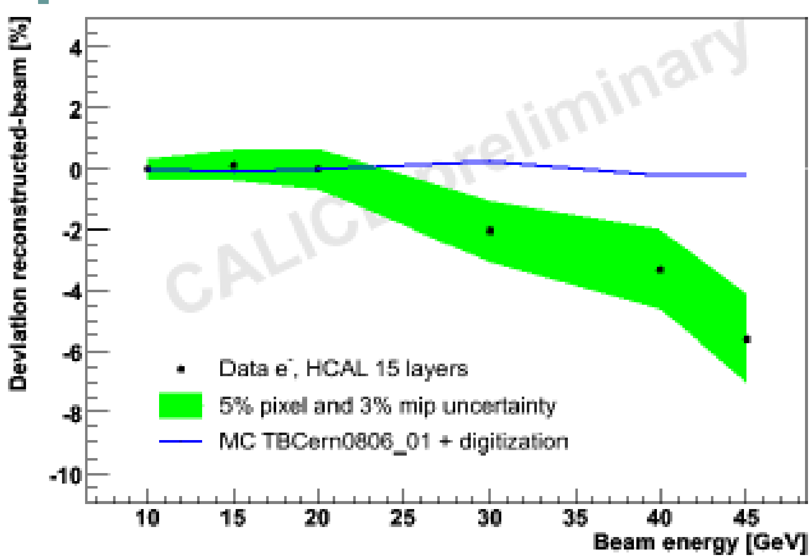


Gap between PCB and W layer increases $R_M(W) \rightarrow R_M(eff)$

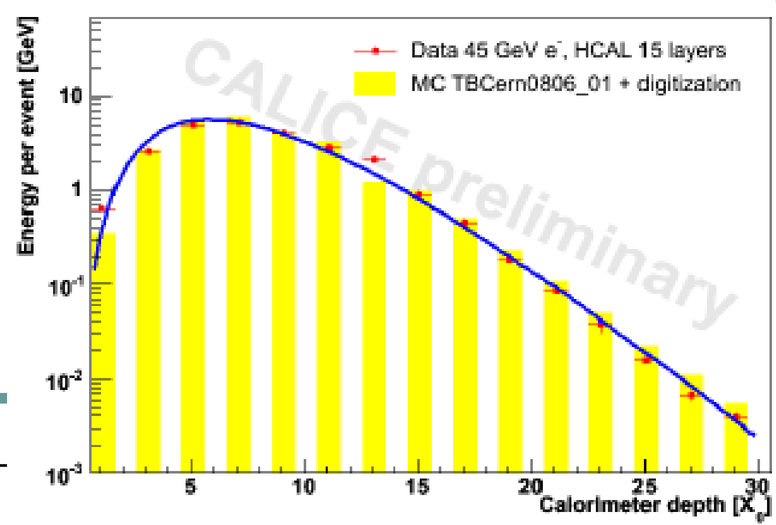
AHCAL response to electrons

- AHCAL alone (15 layers)
- Remove hits below 0.5 mip
- Energy sum of whole AHCAL, fit mean response
- Linearity better than 6%



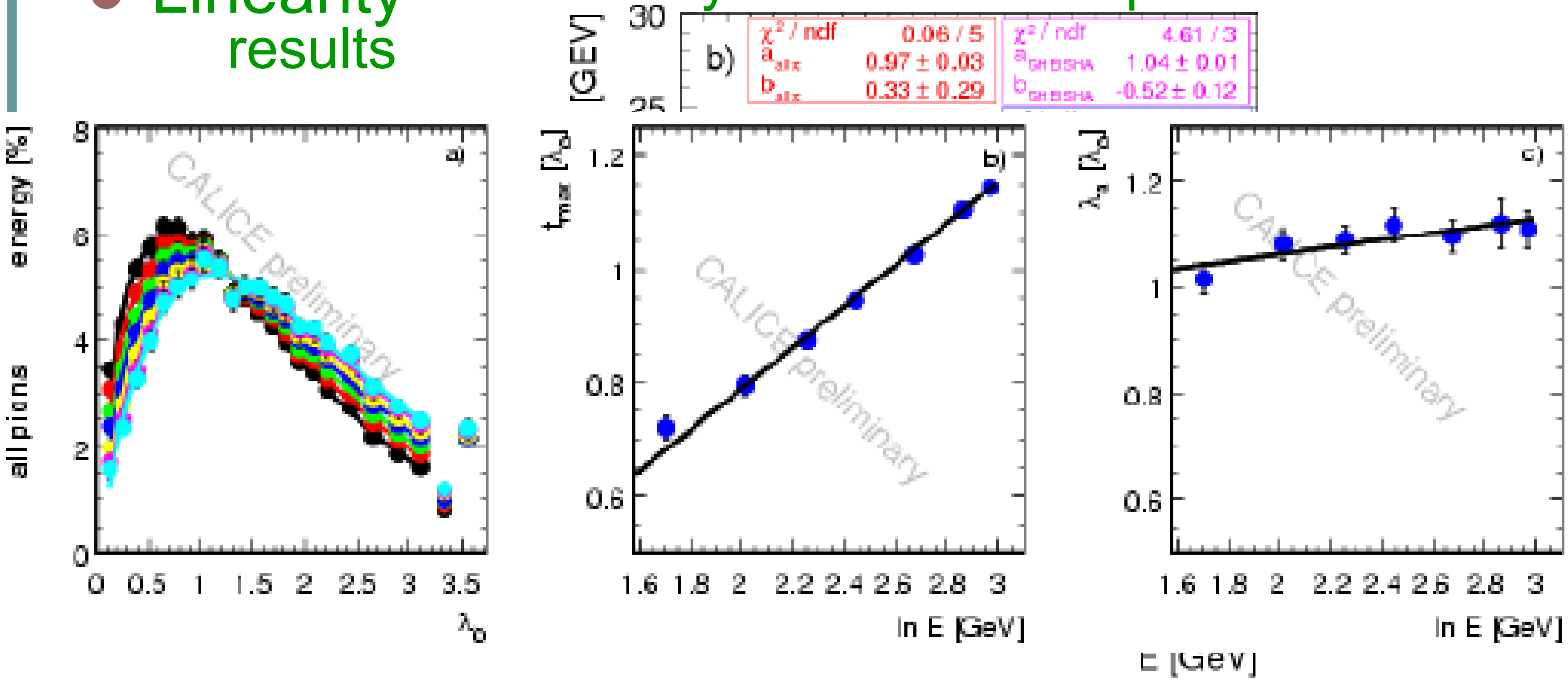


- Longitudinal energy profile



Response to pions

- Longitudinal shower development
- Energy sum compared between data and MC
- similar conclusion as EM showers
  - GEISHA (no neutron transport)
  - CALOR/FLUKA/MICAP (full neutron response)
  - General trend as expected
- Linearity
  - More detailed analysis needed for quantitative results



Summary of 2006 test beam

- Analysis of 2006 data well under way
  - More than 9TB of data to analyze !
- Excellent performance of the ECAL
  - Very encouraging preliminary results on resolution, linearity and longitudinal shower development
- First results from e/π AHCAL results
  - Encouraging results for EM studies
  - Promising results from pion beam data
- Expect first publications by end of this year

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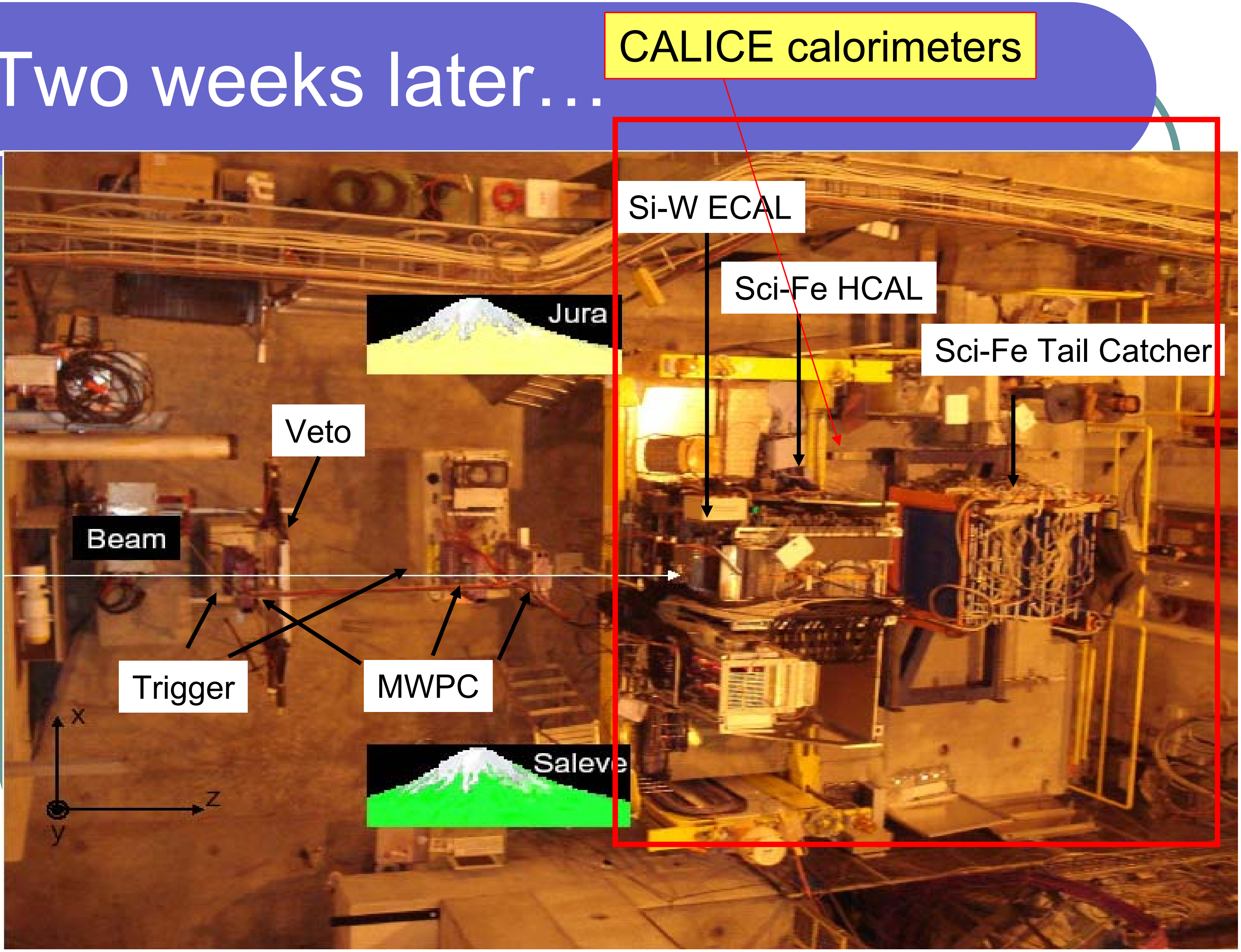
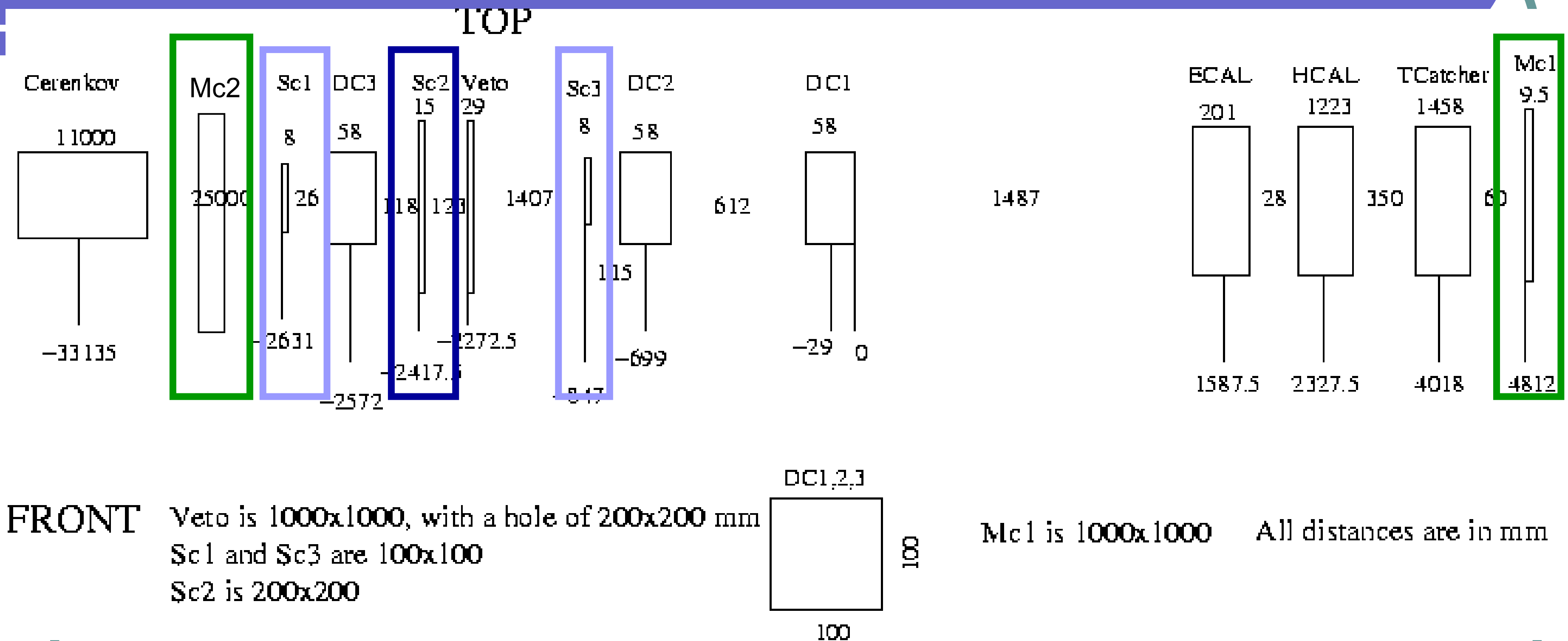
A difficult start….

June 07 – from DESY to CERN

Two weeks later…



Beam line setup



- Sc1+Sc3 -> 10x10cm^2 beamData trigger
- Sc2 -> 20x20cm^2 muon calibration trigger
- Mc1+Mc2 (placed on beam line only for muon calibration runs) -> 100x100cm^2 calibration trigger

The CERN beam

- Excellent beam
  - Super-cycle:
    - 14 bp/16.8 sec day
    - (17 bp/20.4 sec from 15/08)
    - 12 bp/14.4 sec night/w-e
- Secondary beam energies:

-80 GeV wobbling	π^- (40-100 GeV) and e^- (15-50 GeV)
-10 GeV wobbling	π^- and e^- (6-25 GeV)
+60 GeV wobbling	π^+/p(30-80 GeV) and e^+ (10-50 GeV)
-130 GeV wobbling	π^- (60-180 GeV) and e^- (70-90 GeV)

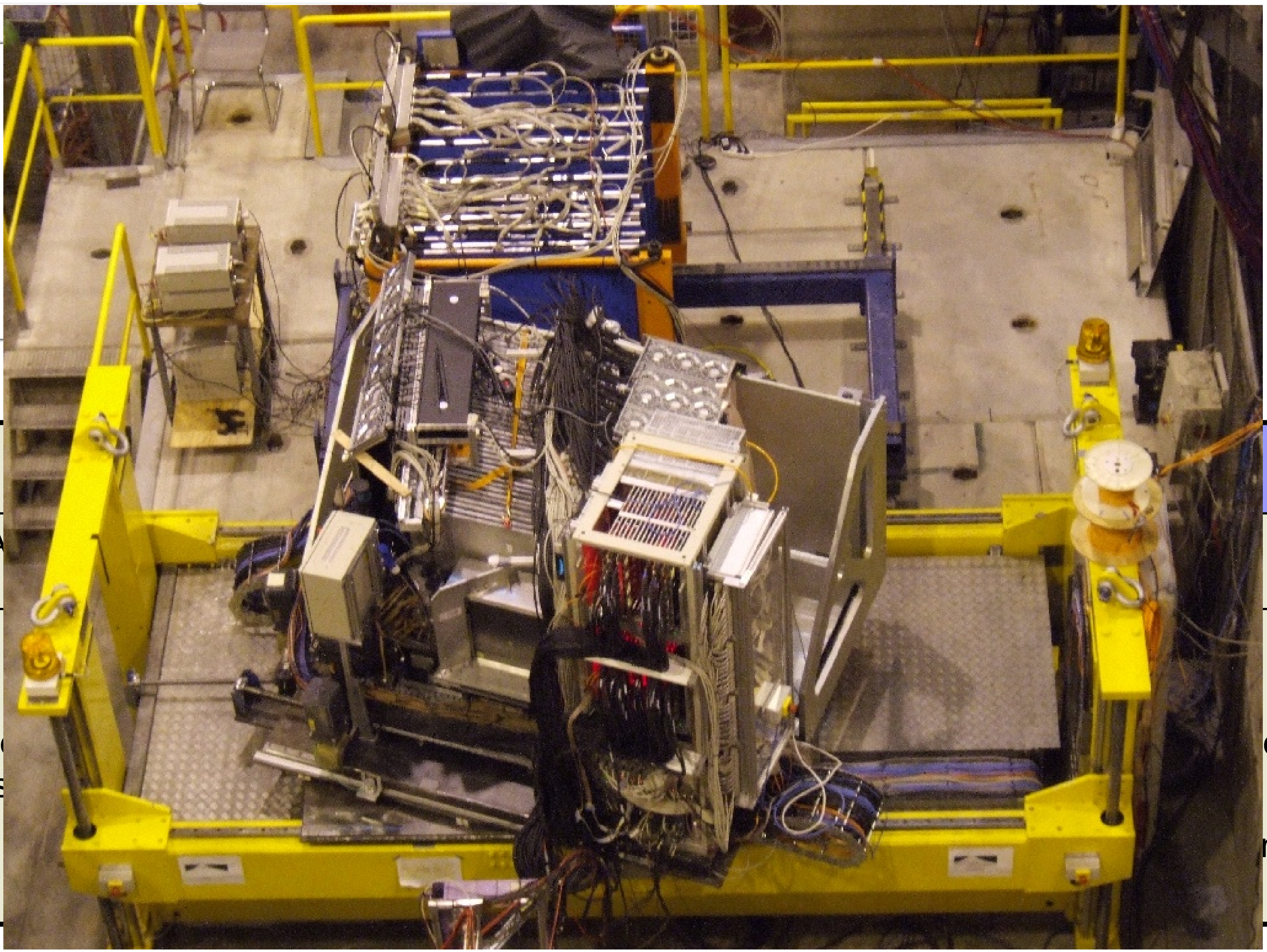
The test beam programme: energies and particle types

- Very intense test beam programme
  - 7 weeks of continuous data taking (July 5th → August 22nd)

	Proposed in TB plan	Collected during TB
Energy (GeV)	6,8,10,12,15,18,20,25,30,40,50,60,80	6,8,10,12,15,18,20,25,30,40,50, 60,80,100,120,130,150,180
Particles	$\pi^{\pm}/e^{\pm}$	$\pi^{\pm}/e^{\pm}$/protons

- π/e (π/p) separation achieved using Cherenkov threshold detector filled with He (N_2) gas
  - Possible to distinguish π from e(p) for energies from 25 to 6 (80 to 30) GeV

The test beam programme: angles and position scans



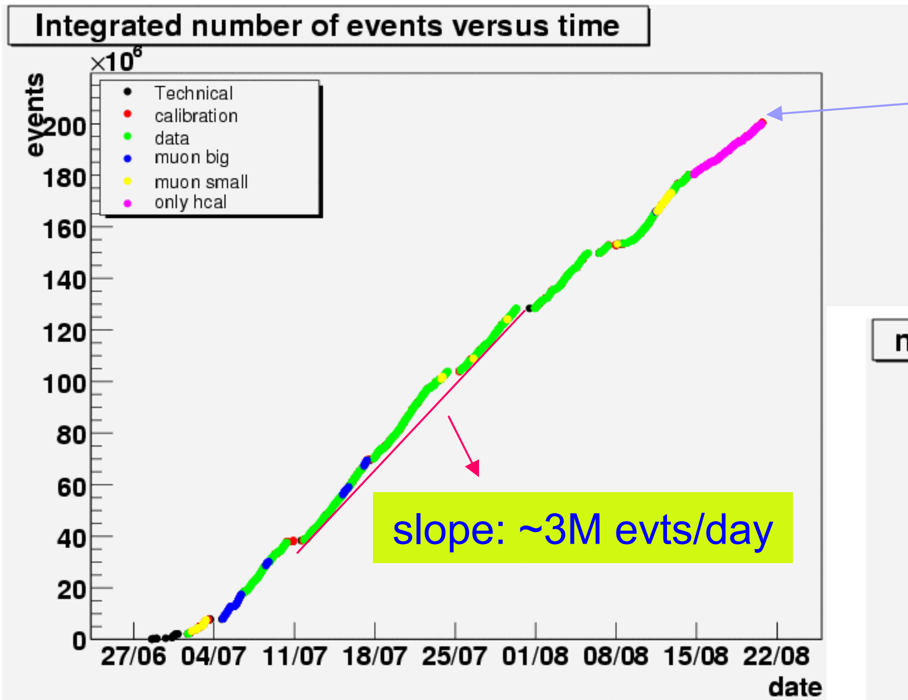
A

P
s

cm)

m-line

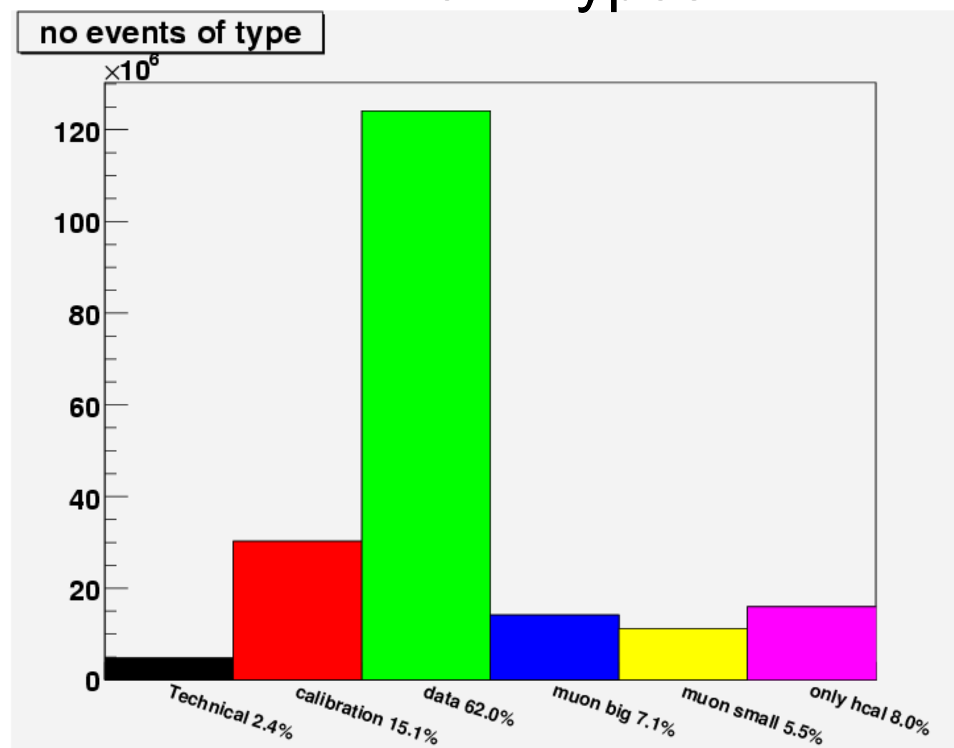
Total events collected



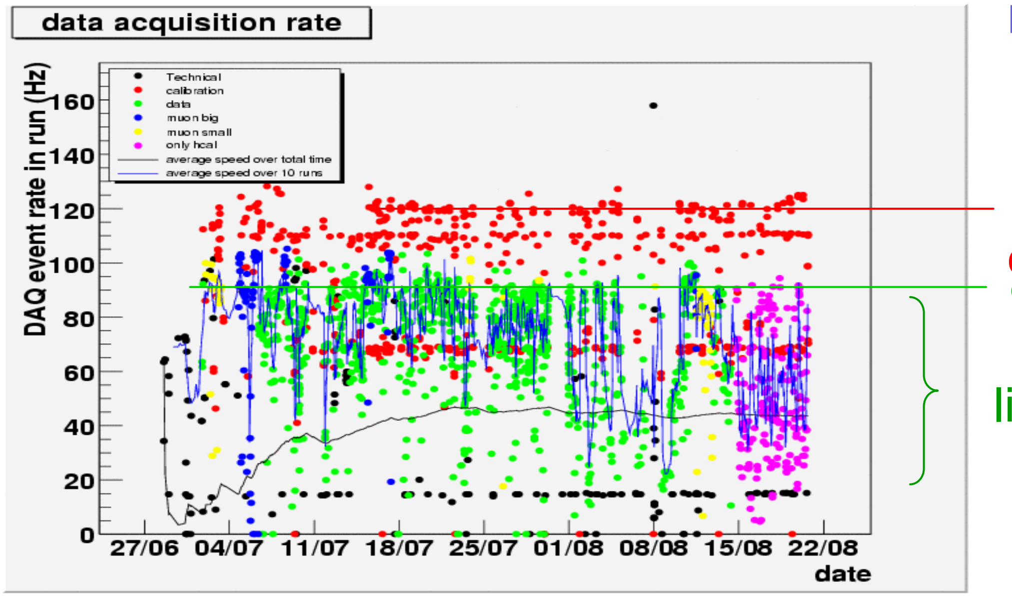
200M triggers !!!

Total Events vs Time

Event Types

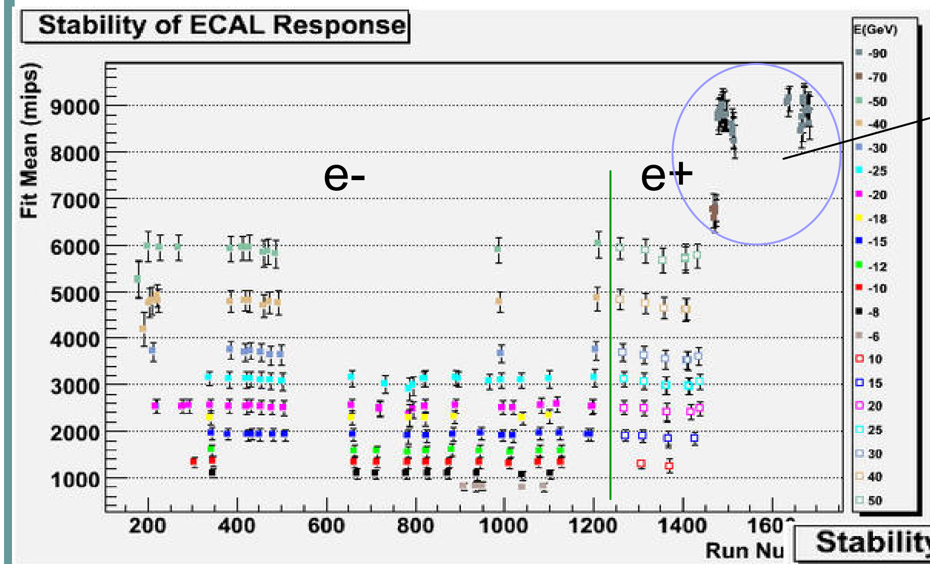


DAQ rate



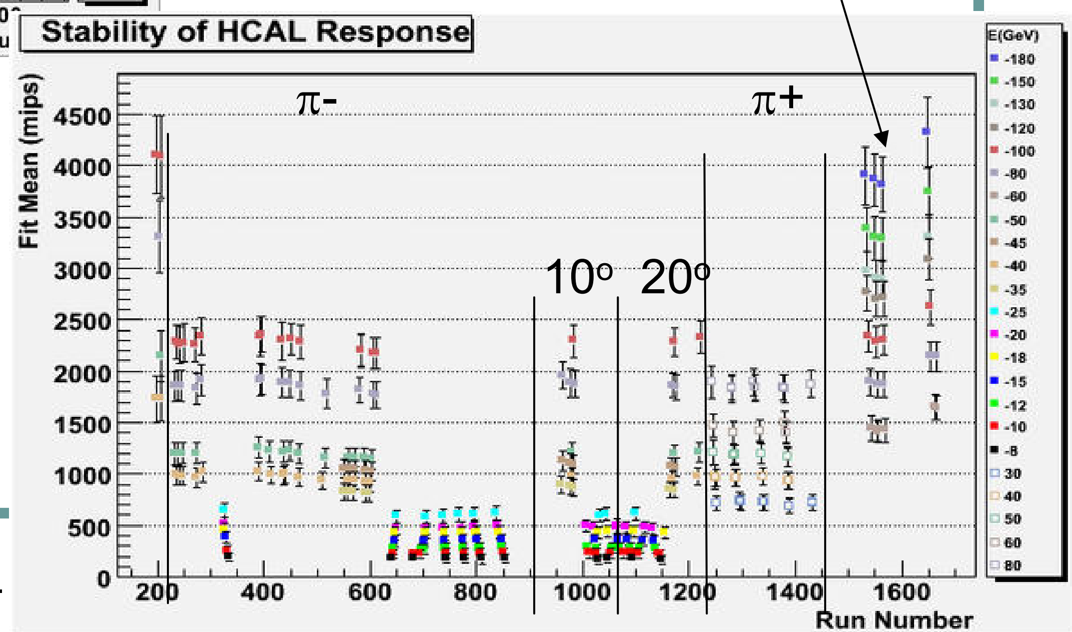
- Low energy beams (6-25 GeV)
  - Trigger rate on 10x10 adjusted in beam files using available collimators
    - Average rate ~ 600 pps@ 6 GeV,
      ~1-3K pps@ 8-25 GeV
  - DAQ rate ~35-60 Hz
- High energy beams (30-180 GeV)
  - Trigger rate on 10x10 set to <10K pps to prevent damage to the detectors
    - Average rate ~8K pps
  - DAQ rate ~70-80 Hz

ECAL and AHCAL response



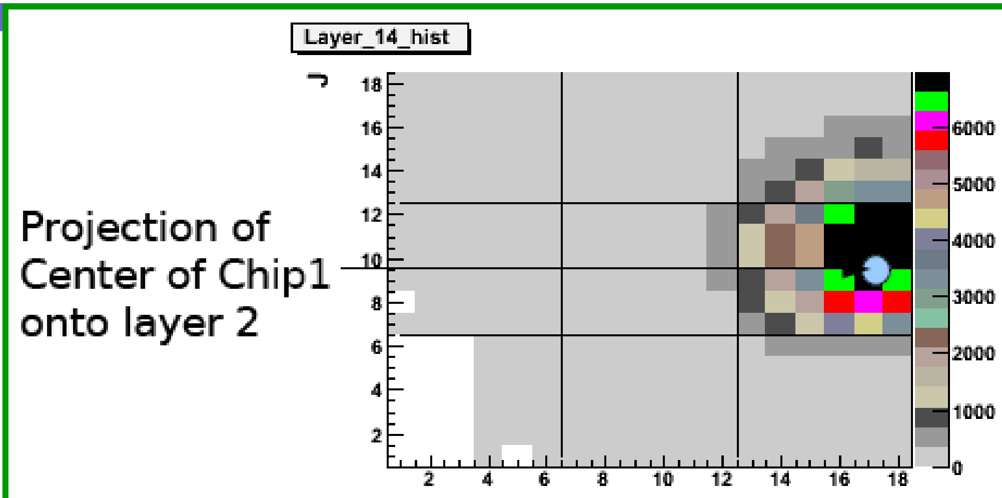
Irradiation of one PCB
(see next slide)

AHCAL alone runs

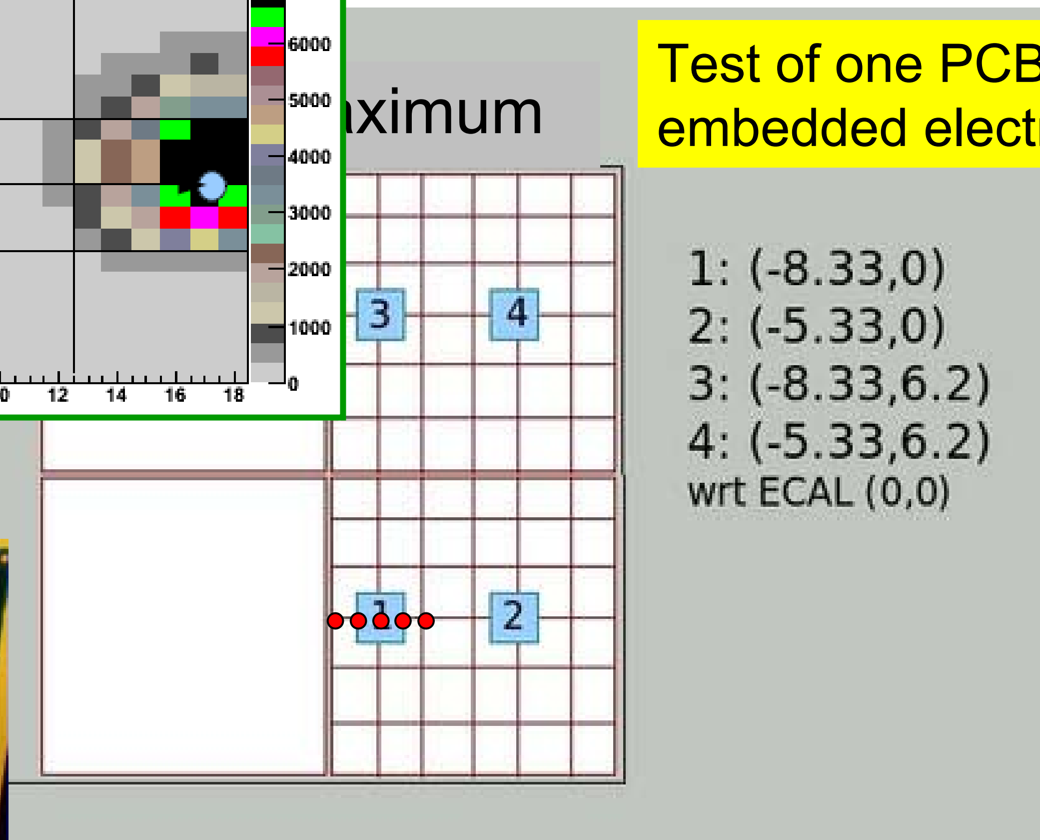


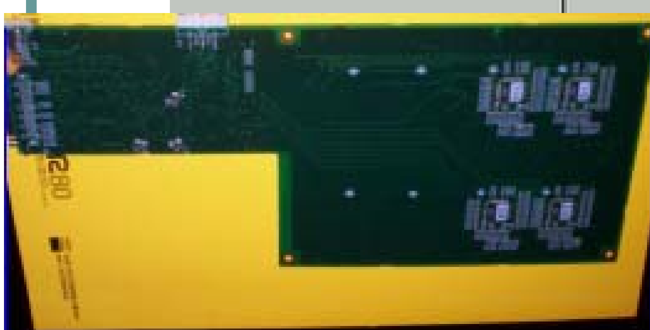
Plots made during shifts,
no corrections applied

Irradiation of ECAL PCB



Test of one PCB with embedded electronics

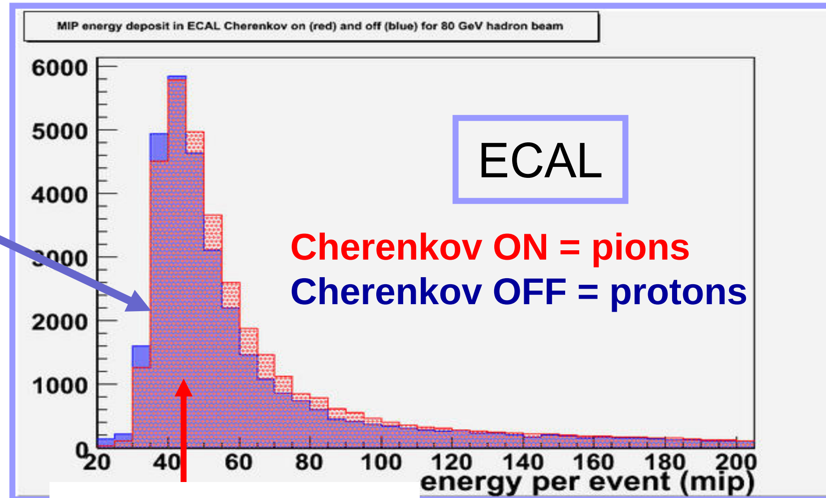




5 position scan for each of the 4 chips on the special ECAL slab
- 90 (and 70) GeV electron beam used
~1.2 M events per chip

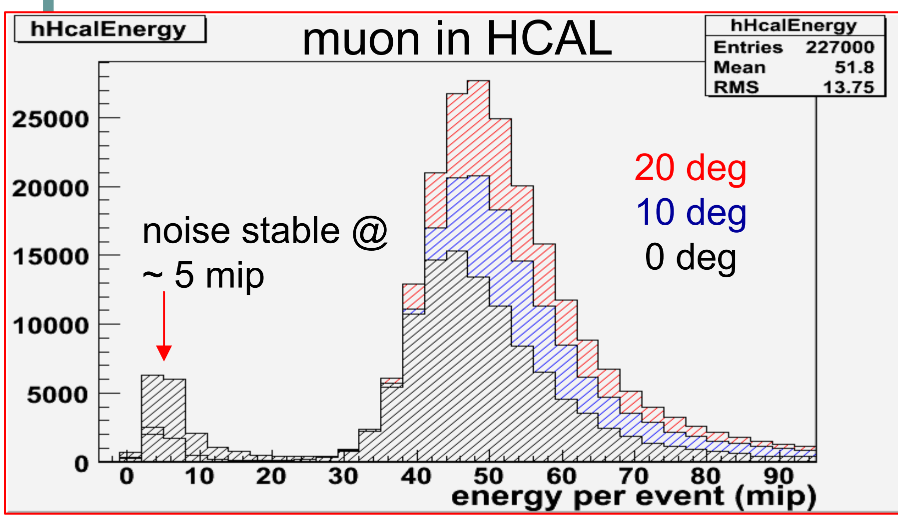
CALO response to p/μ beam

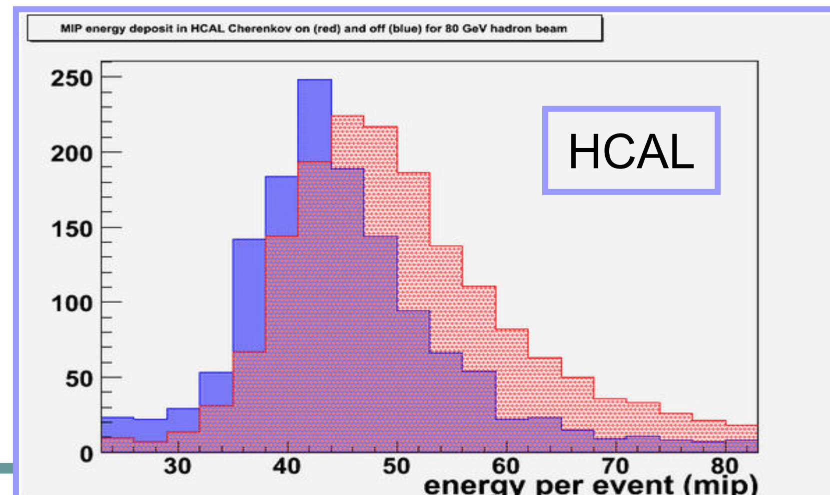
ECAL and AHCAL response to π and protons, distinguished using signal from Cherenkov detector



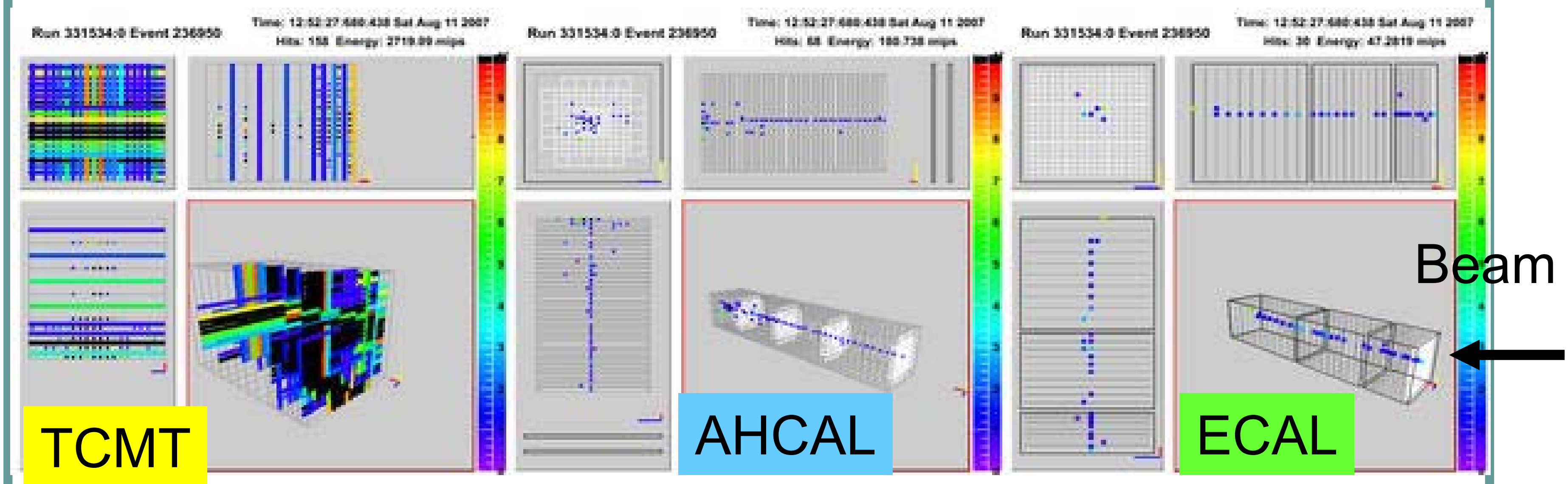
1 mip-like particle

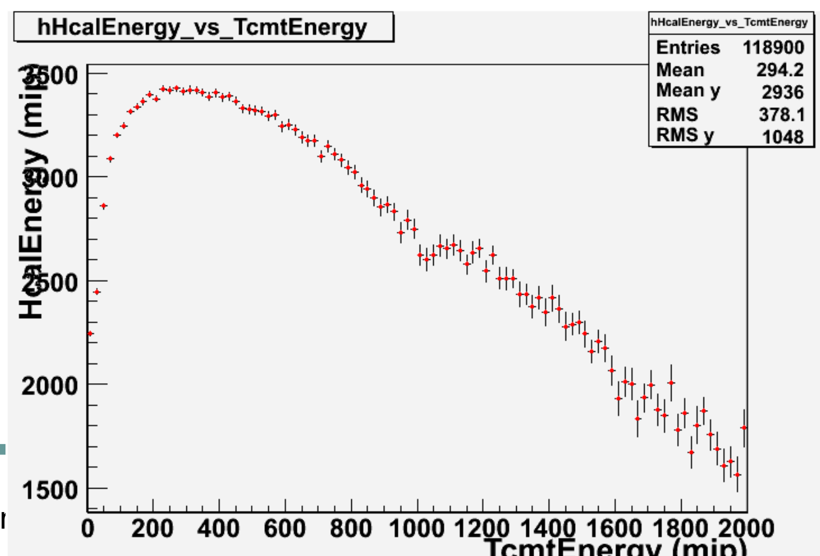
AHCAL calibration performed using samples of several million muons at the different angles





TCMT response





180 GeV pion
strong AHCAL-TCMT anti-correlation

Summary of data taking time

Time since 5th of July	4 147 200 sec
14.4s super-cycle	2 389 798 sec
16.6s (20.4s) super-cycle	889 829 sec
Power cuts	86 400 sec
Summer students	57 600 sec
π/e/p data	1 790 698 sec
muons (100x100)	153 976 sec
muons (20x20)	131 752 sec
AHCAL only	365 195 sec
Calibration	318 447 sec
SPS up-time	79.1%
Beam controlled by H6B	76.1% (96.2% of up time)
DAQ taking analysis data	62% (81.5% of beam in H6B)
DAQ on calibration	15.1%

Summary of the 2007 test beam

- This year's test beam has been a huge success !
- The test beam programme has been completely fulfilled, thanks to the hard work of everyone involved and to the extra weeks given to us by CERN
- The participation in the test beam has been incredible and full of enthusiasm from everyone in the collaboration
- We have ~14 TB of data available on the grid ready to be analyzed

Analysis of 2007 data under way

- Analysis of 2007 test beam data has started
  - ECAL
    - Physics performances: linearity and resol
    - Detector performances: study of no ctors
    - Irradiation of test PCB with in ctronics
    - Particle flow algorithm B data
  - AHCAL+TCMT
    - Detector s: calibration of SiPM
    - emperature dependence of SiPM signal
    - performances: linearity and resolution
    - mparison with existing MC models: characterization of electromagnetic and hadronic showers

Eagerly awaited by all ILC community !

Outline

- The 2006 CERN test beam
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- Conclusions and Outlook

The next test beam at FNAL

CERN test	Proposed plan for the test beam (4 weeks)	Achieved results at the test beam (7 weeks)
Particle type	$\pi^-(\pi^+)$, $e^-(e^+)$	$\pi^{+/-}$, $e^{+/-}$, protons.
Energy points (GeV)	6 - 80	6 - 180
Angles (deg)	0, 10, 15, 20, 30	0, 10, 20, 30

Preliminary ideas for the test at FermiLab:

- Low energy points: E < 6 GeV, $e/\pi/p$ (minimum E = 0.5 GeV)
- Integration of prototypes: test of SiW/SciW-ECAL+AHCAL/DHCAL
- Physics program: establish data set for comparison with CERN data and AHCAL/DHCAL data
- Angles: 15 deg. (missing in 07 tb), 30 deg. ECAL+AHCAL
- Technical studies: ECAL noise, integrated chip, AHCAL long term stability…
- …

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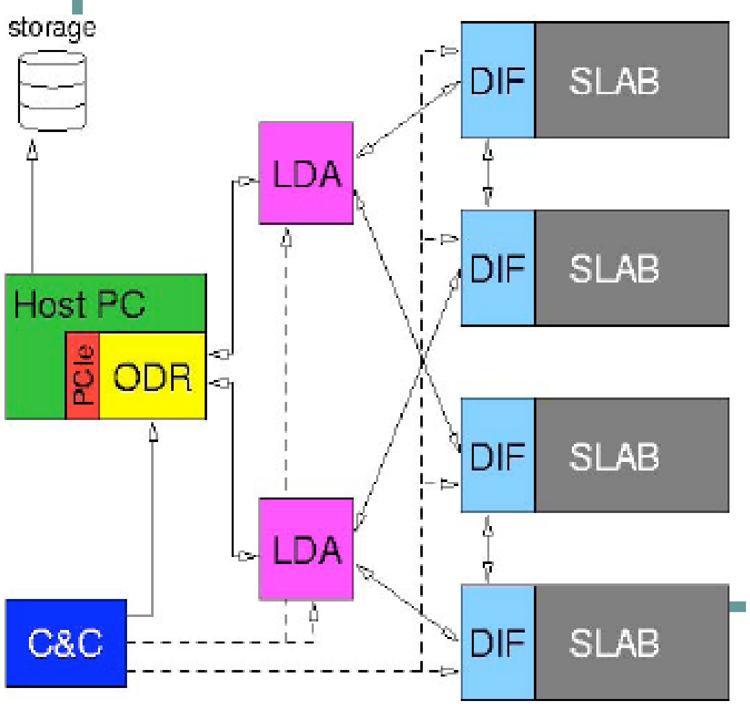
Towards a DAQ for the ILC

- The UK plays a major role in the design and development of a Data Acquisition for the final ILC detectors
- Based on the idea developed in CALICE R&D, i.e. common DAQ for all detectors



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Off-Detector Receive
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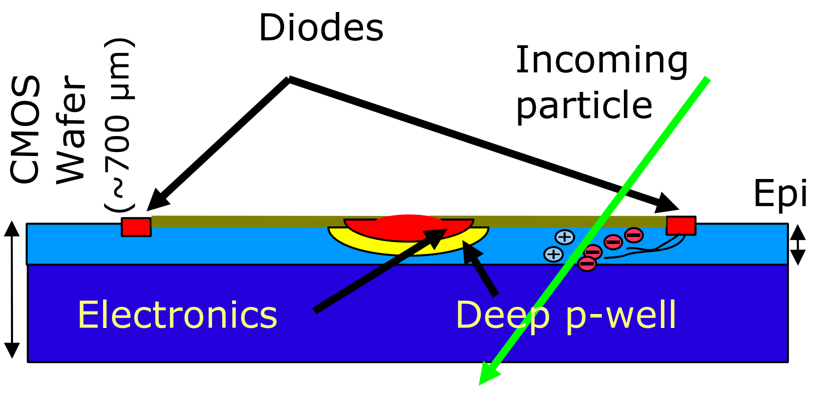
F. Salvatore, RHUL

- ODR: commercial FPGA board
- Custom made firm- and software

- LDA: commercial FPGA board
- Custom made add-ons
  - Gbit ethernet to ODR
  - Many links to DIFs

MAPS ECAL Design

- Monolithic Active Pixel Sensors
  - Alternative readout sensor for the Calice ECAL
  - High granularity and digital readout
  - CMOS manufacturing: now a mature technology
- “Swap-In”: leaving mechanical structure untouched



- Specific Design for Calice
  - Pixel Size 50 x 50 µm^2 (10^{12} for ECAL)
  - Binary readout: 1 bit ADC realized as comparator
  - 4 diodes for charge collection
  - 13 bit time stamping
  - Hit buffering for entire bunch train
  - Capability to mask individual pixels
  - Threshold adjustment for each pixel

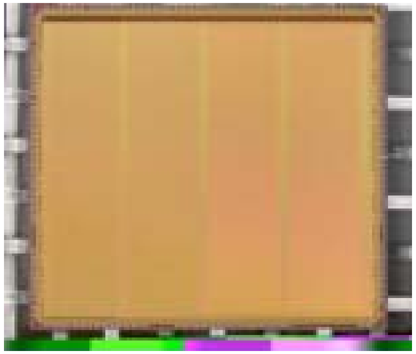
• Sensor and electronics in one wafer
• Charge collection in epi-layer
  • Charge collected by diffusion
• n-well isolated with 3 µm thick “deep p-well”
• Novel *INMAPS* process for the CALICE MAPS

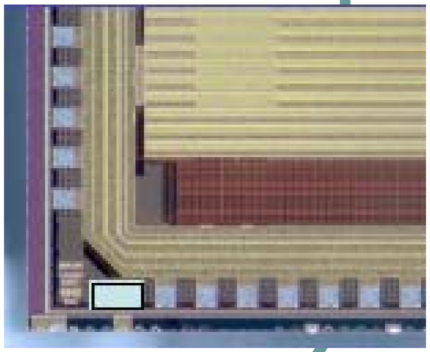
Plans for prototype testing

- Test sensors delivered this summer
- First test are being carried out
  - Charge diffusion using laser setup @ RAL
    - 1064, 532 & 355 nm wavelength
    - Focusing < 2μm
    - 4ns pulse, 50Hz rep. rate
    - Fully automated
  - Cosmic and source setup provided by Imperial and Birmingham

Test Sensor
Area of 1 x 1 cm^2 ~ 28,000 pixels
Testing different architectures n-well or p-well

Extensive simulation studies
Charge collection effects
Resolution versus threshold
....





Leading UK role: simulation, design, testing

Particle Flow Algorithms

- PFA measures jet energies by summing up charged track momenta, γ energy deposits in ECAL and neutral hadron energies in HCAL
  - Can PFA meet the ILC performance specs ?

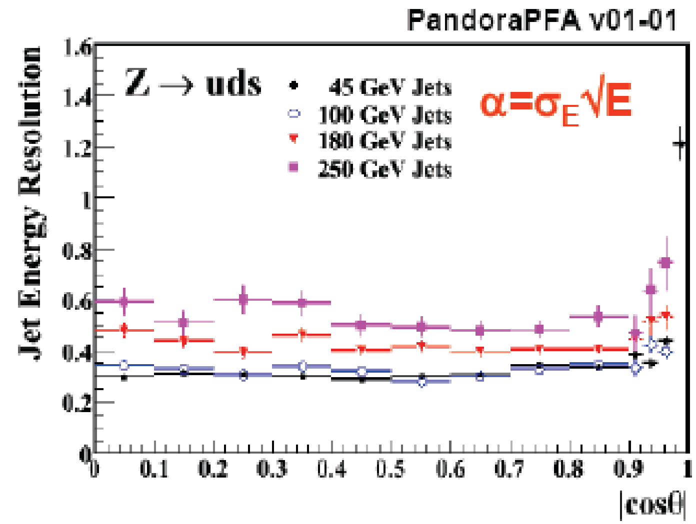
UK has leading role in PFA studies

Mark Thomson's PandoraPFA is a proof of principle that PFA can work !

rms90

E_{JET}	$\sigma_E/E = \alpha\sqrt{(E/GeV)}$ $\lvert\cos\theta\rvert<0.7$
45 GeV	0.295
100 GeV	0.305
180 GeV	0.418
250 GeV	0.534

An excellent start !



- PFAs show the importance of optimizing the integrated detector performance of Magnet+Vertexing+Tracking+Calorimetry

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Conclusions and Outlook

- The CALICE collaboration is very healthy !
- We are entering in the publications phase
  - Two papers are being prepared on the 2006 test beam, and will be out by the end of the year
  - Analysis on the 2007 data is well under way
- Ready for our next phase of beam tests
  - Preliminary discussion on next year's tb programme already started
- We are growing !
  - Three new institutes asked to join last month
- Lot's of involvement in the UK
  - UK is taking a major role in test beam and DAQ studies for the ILC
  - MAPS technology, if proven, could take the UK to a leading role in the development of the next generation calorimeters