HADRON SHOWER PROPERTIES AT ENERGIES 8-80 GEV

1. MOTIVATION
2. IMAGING CALORIMETERS
3. HADRON SHOWER MEASUREMENT
4. FUTURE
5. CONCLUSIONS

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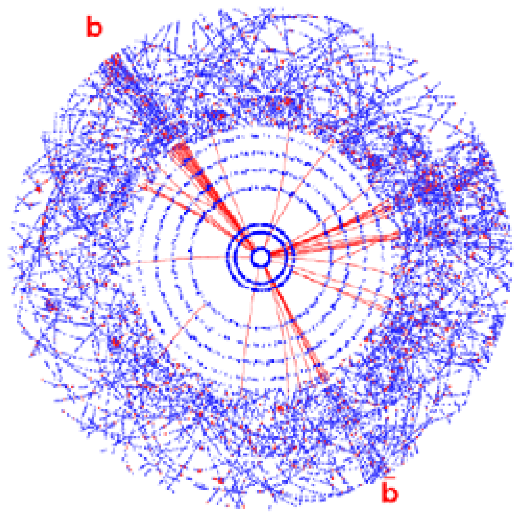
1. Motivation

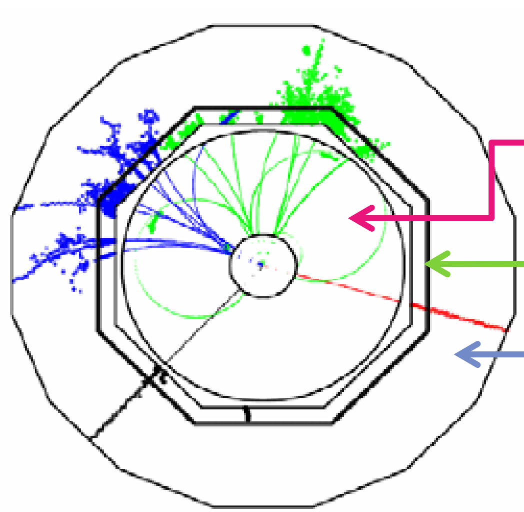
Higgs production at Large Hadron Collider (7 TeV, CERN) and International Linear Collider (0.5 TeV, ?)

★ **Electron-positron colliders provide clean environment for precision physics**

The LHC $\mathrm{pp} \to \mathrm{H} + X$

The ILC $\mathrm{e}^{+}\mathrm{e}^{-} \to \mathrm{HZ}$





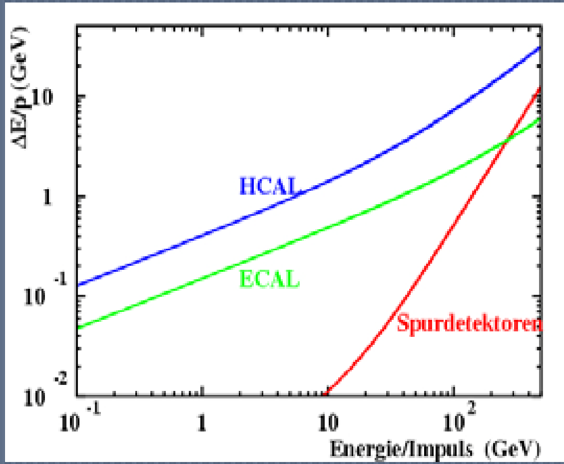
Background-free production of interesting events à high precision physics

- Tracker
- Electromagnetic calorimeter (ECAL)
- Hadron calorimeter (HCAL)

★ **At electron-positron the final state corresponds to the underlying physics interaction, e.g. above see** $\mathrm{H} \to b\bar{b}$ **and** $\mathrm{Z} \to \mu^{+}\mu^{-}$ **and nothing else…**

High precision LC physics demands a high precision detector:
- high precision vertex (flavour tagging) and tracking (Higgs from di-lepton recoil mass)
- precision calorimetry (heavy bosons reconstruction from di-jet decay)

Particle Flow paradigm

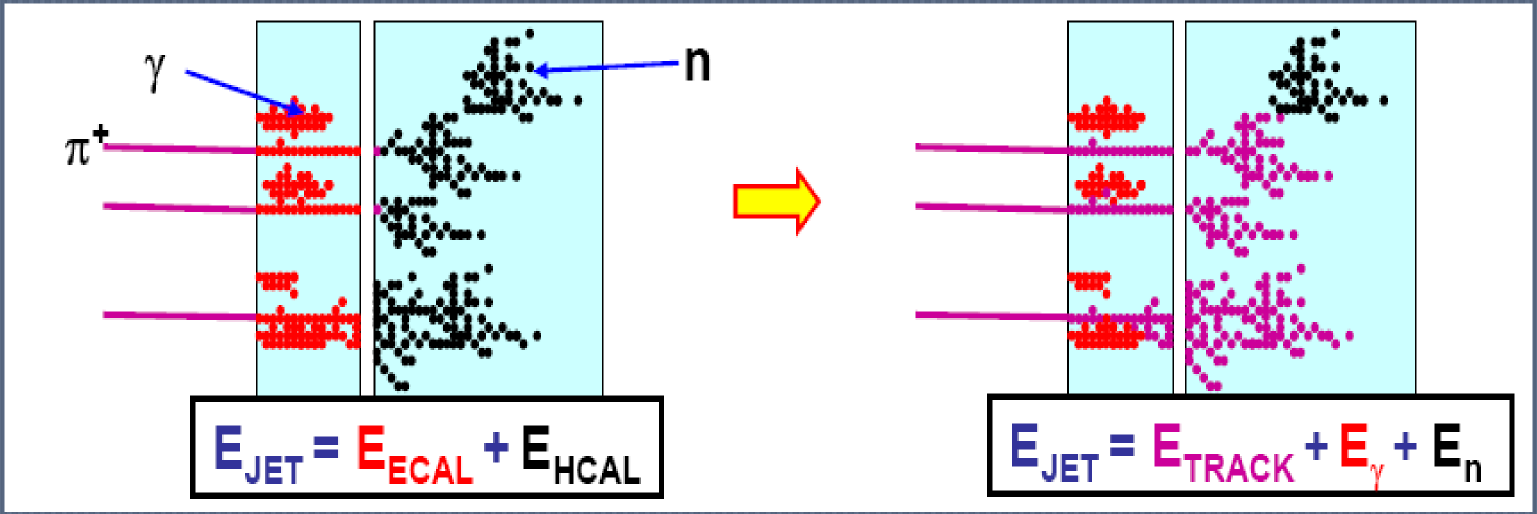


è Reconstruct every particle in the event

- up to ~100 GeV - tracker is superior to calorimeter à
- use tracker to reconstruct e ,m,h (<65%> of E_{jet})
- use ECAL for g reconstruction (<25%>)
- (ECAL+) HCAL for h^0 reconstruction (<10%>)

è HCAL E resolution still dominates E_{jet} resolution

è But much improved resolution (only 10% of E_{jet} in HCAL)



PFLOW calorimetry = Highly granular detectors (CALICE) + Sophisticated reconstruction software

Imaging calorimetry

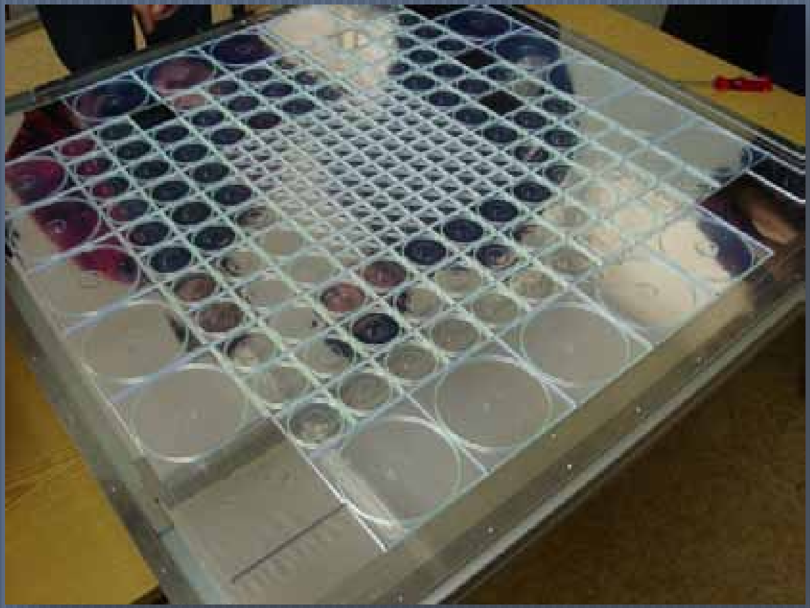
2. Imaging Calorimeters

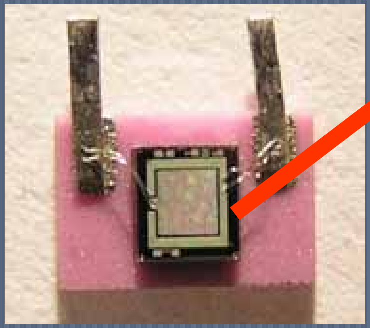
- CALICE Collaboration –
  worldwide calorimeter R&D effort

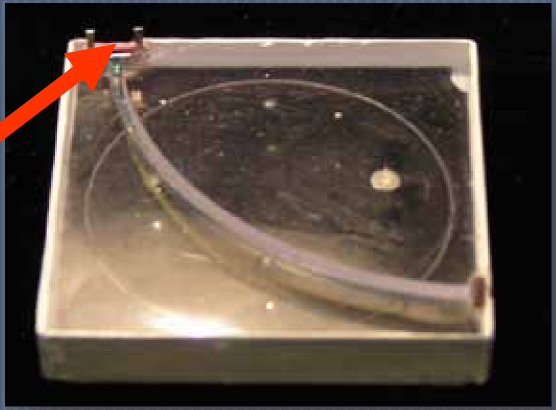
- EUDET – European grant under 6th FP, I3 (2006-10)
  AIDA – European grant under 7th FP, INFRA (2011-14)
- Electromagnetic Calorimeter with W absorber
  - Silicon pads 1 x 1 cm^2 à 0.5 x 0.5 cm^2
  - Scintillator strips 1 x 4 x 0.35 cm^3 with MPPC readout
- Hadron Calorimeter with steel (W) absorber
  - Scintillator tiles with analogue readout
  - RPC / Micromegas / GEM – with digital readout
- Muon Tail Catcher – steel absorber and scintillator strips
- Coordinated test beam programme to combine different technologies at the same time and prove Particle flow paradigm

Scintillator-steel HCAL

- Absorber
  - 38 layers of steel, 2 cm thick
  - 4.5 λ_{int} in total
- Active element
  - Scintillator tiles 3x3 – 12x12 cm^2 with embedded WLS fibres
  - Multi-pixel Geiger mode photo-diodes (SiPMs), B-field proof, small, affordable, integrated
- Read-out chip
  - 2 gains (normal, calibration)
  - HV settings for SiPMs
  - Shaping and multiplexing
  - Power consumption 200 mW/5 V
- Calibration and monitoring by LED flashes, temp. recorded
- In beam 2006-9

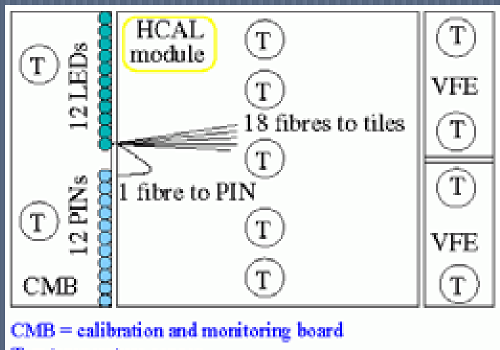


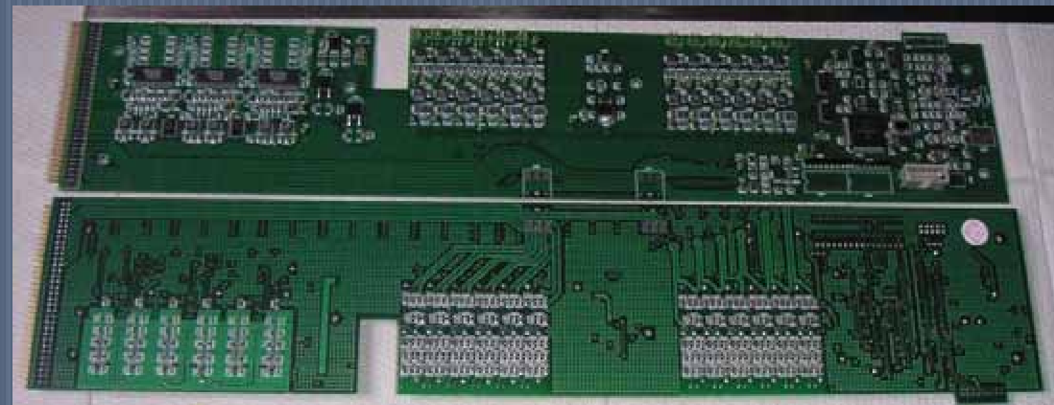


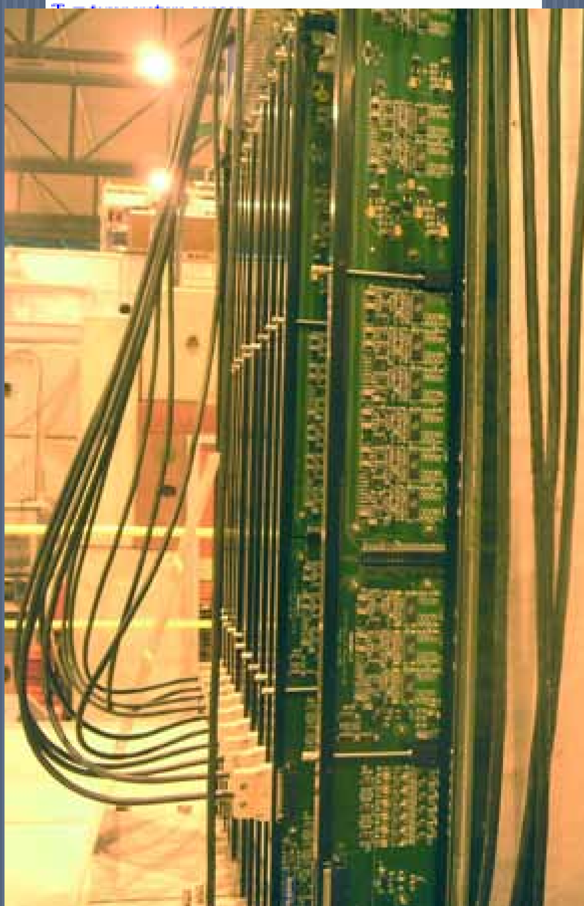


2010 JINST 5 P05004

Calibration and monitoring







Prague main contribution

LED calibration system provides ~ns light flashes of variable intensity:

§ Gain measurement of SiPM at low intensity light

§ Measurement of the SiPM response function at high intensity light

One LED illuminates 18 SiPMs and one PIN photodiode to monitor the LED signal, light is distributed via optical fibres

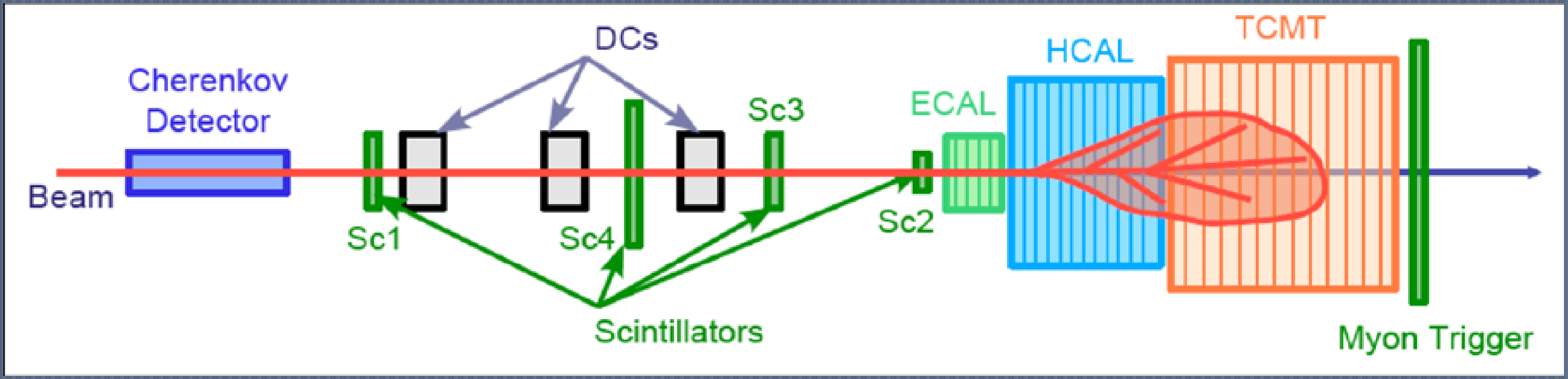
Temperature is monitored by temperature sensors

ã Gain ~ difference between two neighbour multi-photon peaks

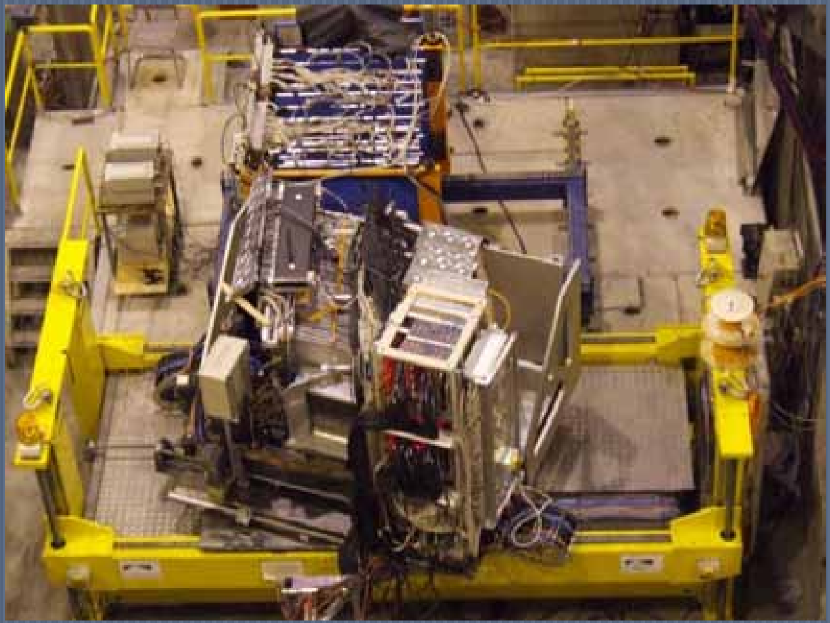
ß Saturation correction

2011 JINST 6 P04003

3. Hadron shower measurement

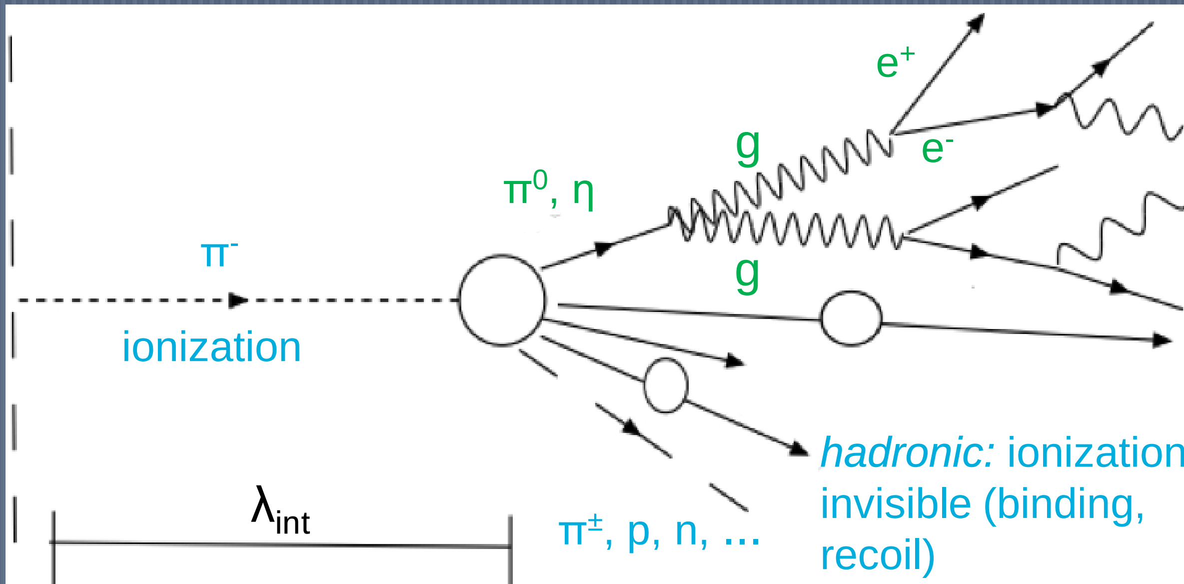


- Extensive test beam program
  - CERN 2006-7
  - FNAL 2008-9
- Beam energies 2-80 GeV
- Particles: μ, π, e, unseparated hadrons, both polarities



Hadron shower

electromagnetic:
ionization, excitation

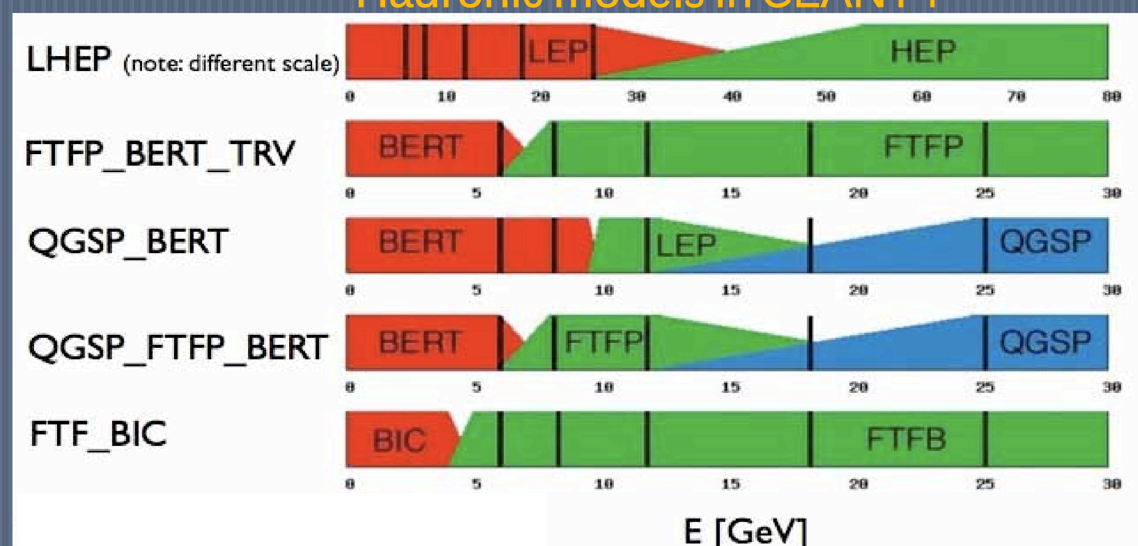


- π absorbed in calorimeter
- Hadron shower: cascade of particles interacting in absorber (~95%) and sensitive medium (~5%)
- Particle energy decreases, finally absorbed in calo material
- This complex process simulated - GEANT4, v. 9.3

Variety of models available to describe hadron showers:

- QGSP_BERT → Bertini cascade à GHEISHA à quark gluon string model
- FTFP_BERT, FTF_BIC → New developments, retuned
- CHIPS → Experimental, no model transition

Hadronic models in GEANT4

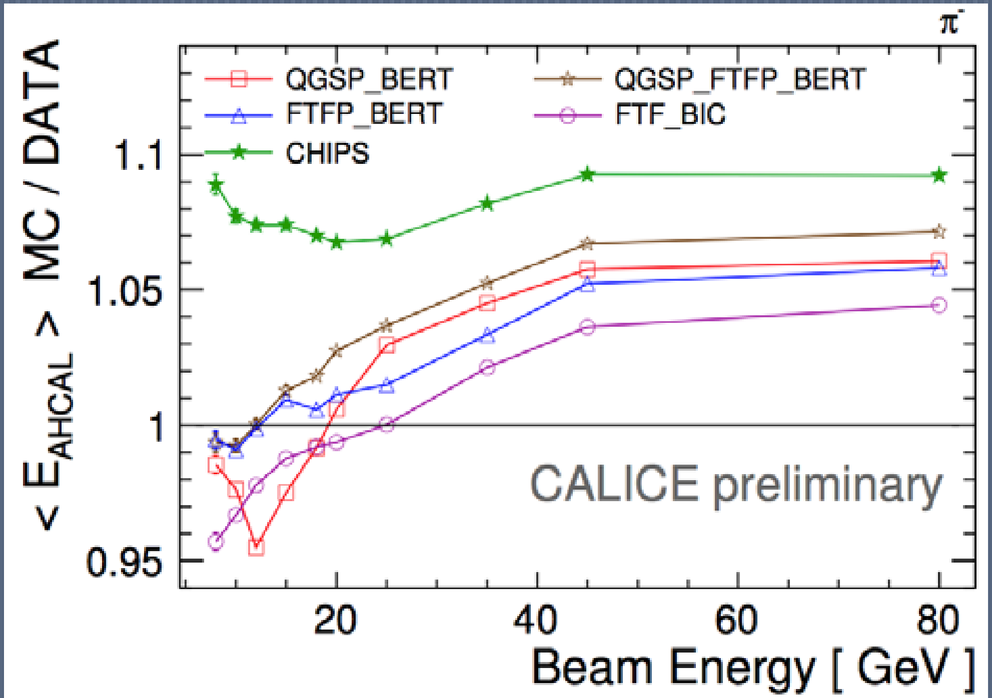


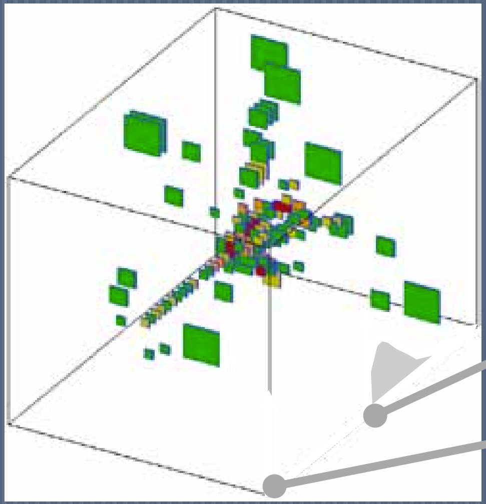
Visible energy

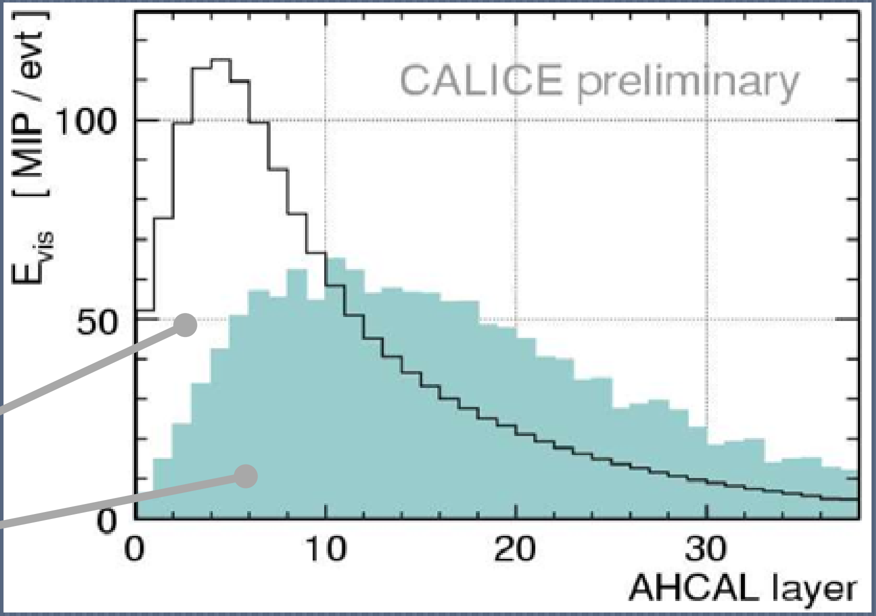
Mean visible energy for p in calorimeter volume

§ QGSP_BERT, FTFP_BERT lower ~ 2% at 8 GeV, overestimate ~ 8% at 80 GeV

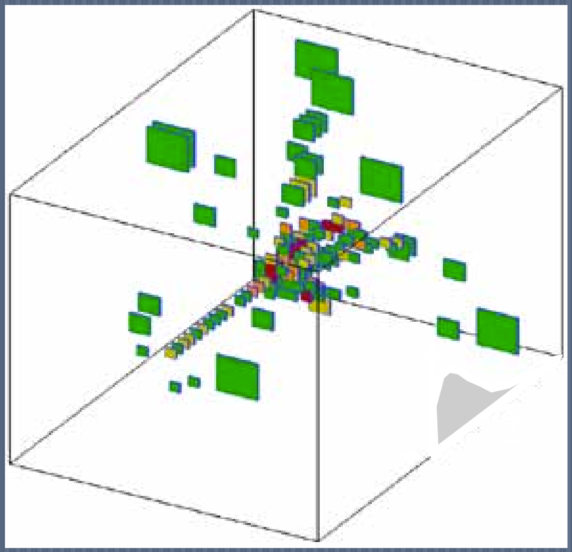
§ CHIPS overestimates ~ 8%, low energy neutron cross-section not yet properly implemented

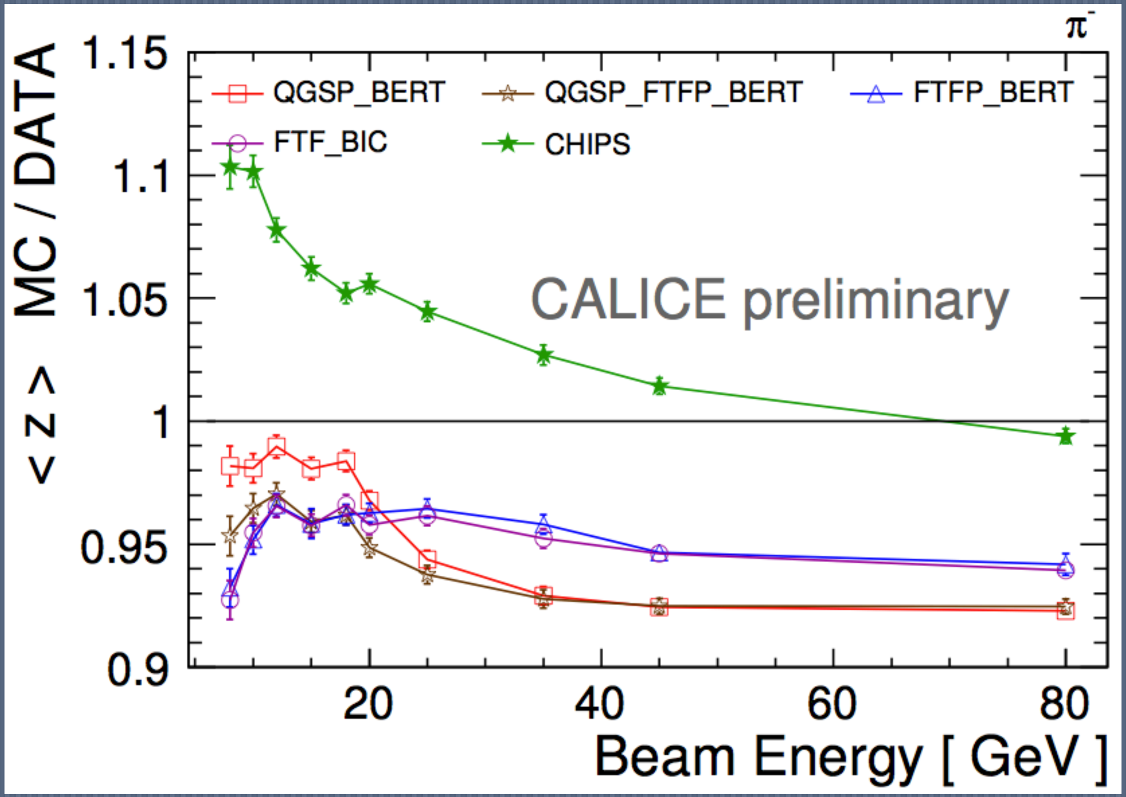






Shower depth





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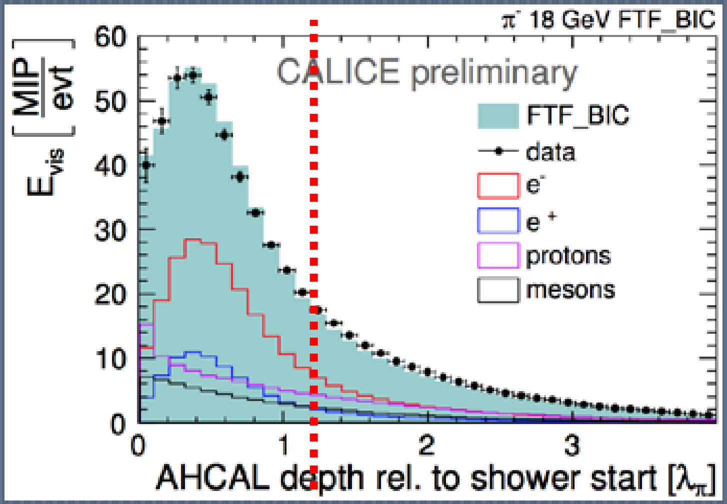
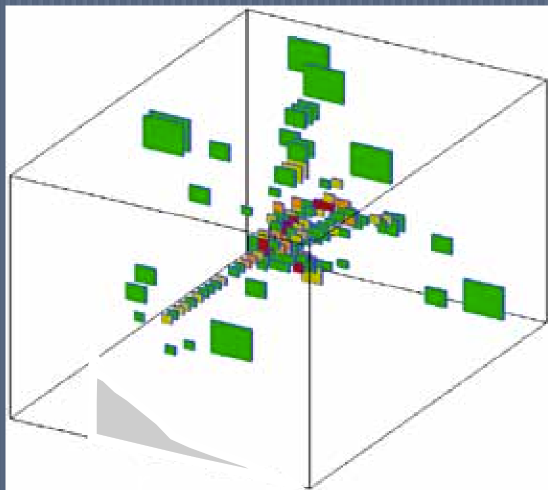
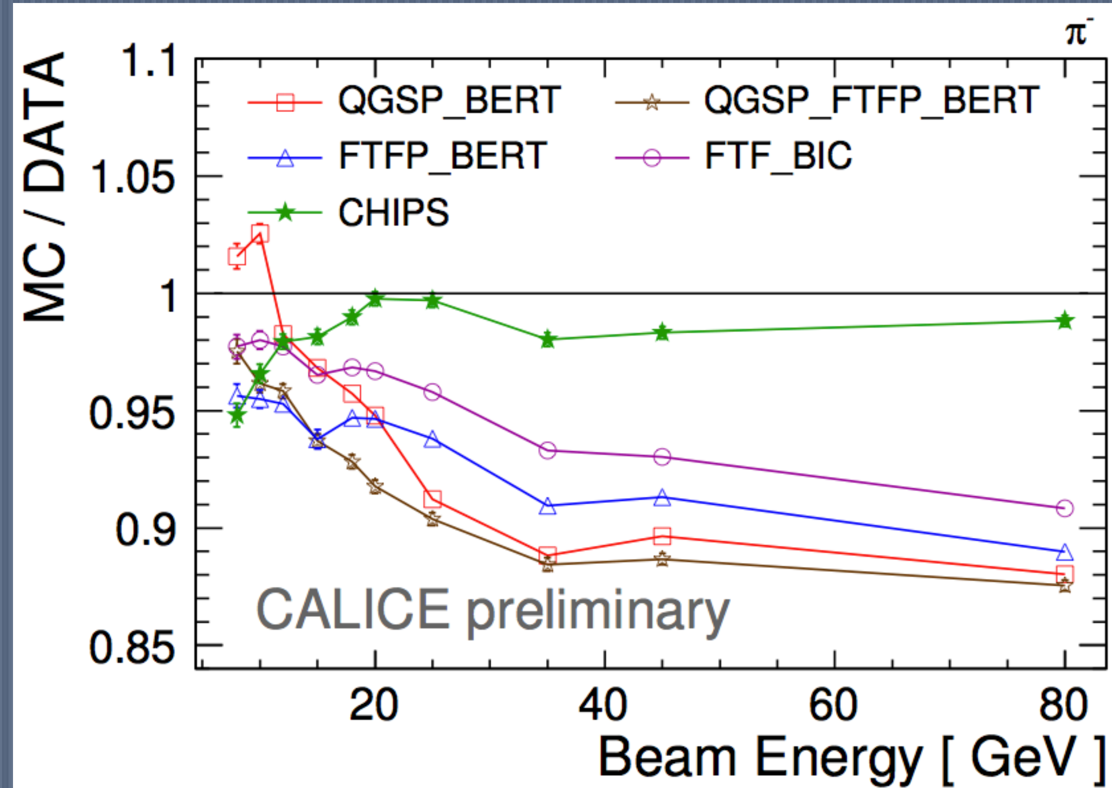
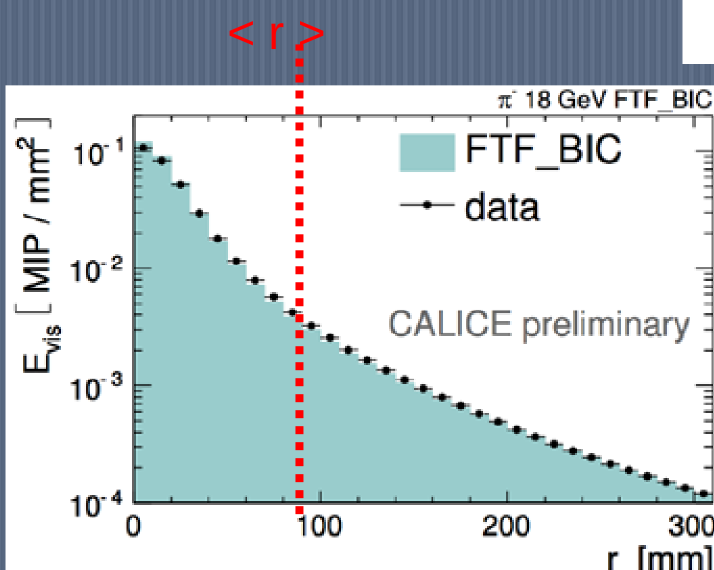


- Similar test to the previous slide
- Variable sensitive to the particle content of the shower:
  - elmg. and hadron shape different
  - protons interact earlier than pions for the same energy
- Shower depth underestimated by FTF and QGS models, CHIPS opposite

Shower radius





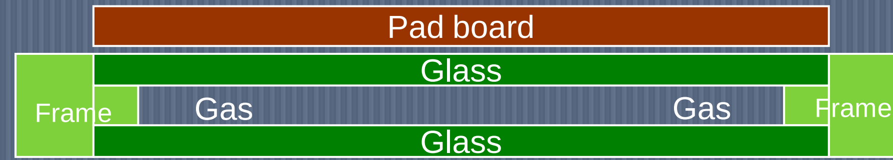


- MC models generally underestimates <r>
- CHIPS model agrees on the ~% level
- Lateral shower profile critical for PFA performance – particle separation

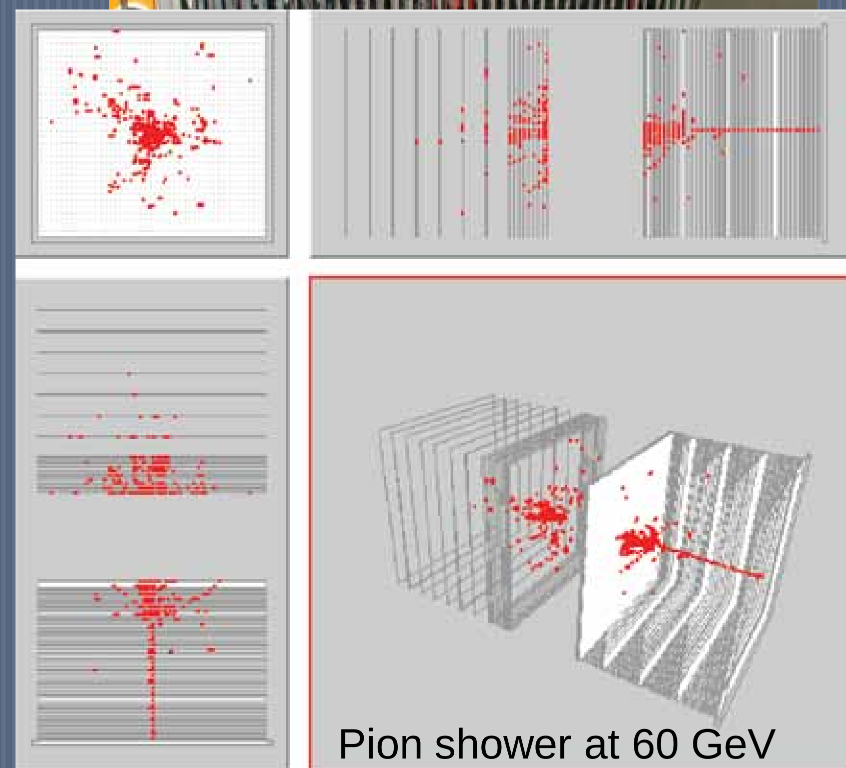
J. Apostolakis etal., EUDET-Memo-2010-5

<r> MC/DATA = 0.95

4.Future

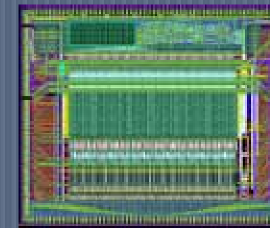


- HCAL with pad size of ~1 cm^2 currently tested in beams (ANL, CNRS) : test new calorimeter concept – digital calorimeter DHCAL
- Showers recorded by Restive Plate Chambers:
  - Gas layer 1.1 mm
  - 2 glass plate painted by high resistivity paint $R_{\square} = 1 - 5\ \mathrm{M\Omega}$
  - Signal read by 1x1 cm2 pads (pad board) with 1 bit (digital) or 2 bits (semidigital) readout
  - Gas gap operates at 6.3 kV
- Construction finished in 2011, test beam 2011-2
- Large teams around ANL (USA) and CNRS (France)
- Main task
  - Validate DHCAL concept
  - Gain experience running large RPC systems
  - Measure hadron showers in large details



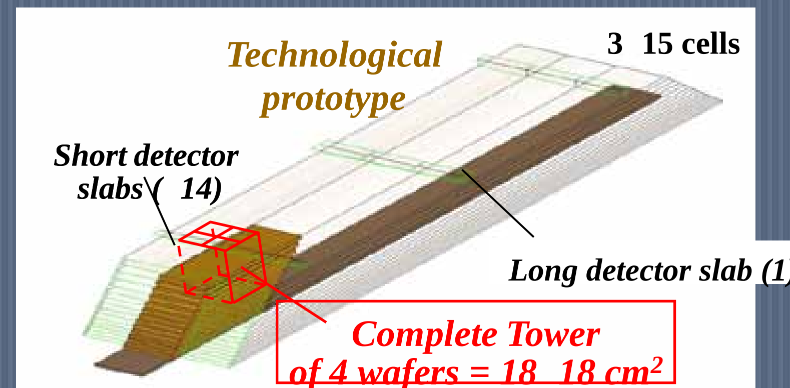
Pion shower at 60 GeV

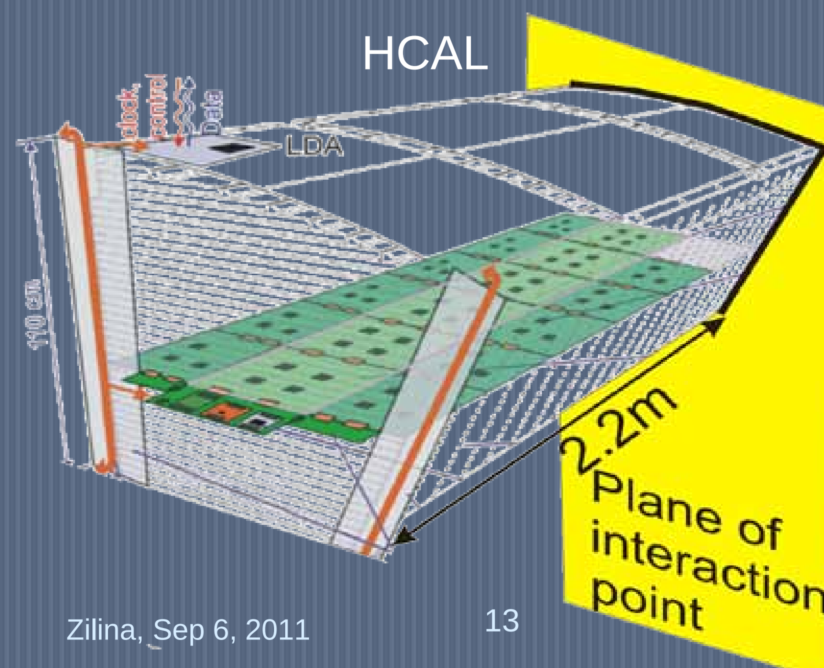
Detector Integration



- From the physics à technological prototypes: technical solutions for the final detector:
- Realistic dimensions: octagonal shape, 16 equivalent wedges
  - Minimal dead space
  - Integrated front/end electronics – new chip with ADC integrated
  - On chip zero suppression
  - Auto-trigger mode
  - Small power consumption
- Construction 2010-2, test beam 2012-4

ECAL





5. Summary, Conclusions

- Calorimeter prototypes with high granularity were built and successfully tested in beams
- New photodetector inserted into scintillator tile – Silicon photomultiplier – is now commercially available and used in many applications
- Imaging calorimetry allows for validation of hadron shower simulations at an unprecedented level of detail
- Comparison of pion shower properties from test beam data and GEANT4 simulation favours FTF based models in the energy range 8-80 GeV
- In the next step of calorimeter R@D, new prototypes will be built which solve problems for construction of the full size calorimeters for the final detector

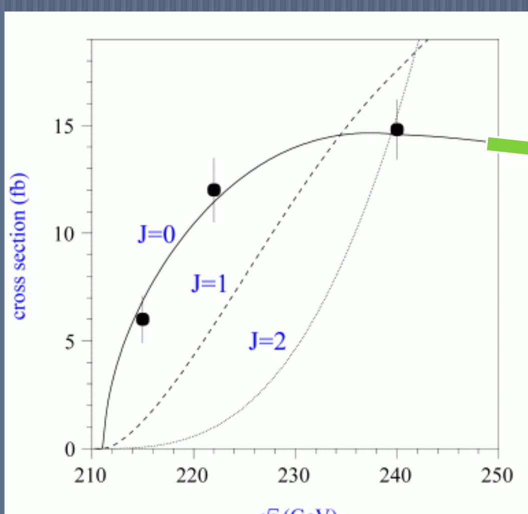
BACK UP

Proč ILC?

- § Přesná fyzikální měření
  - ú polarizace e$^-$ (e$^+$)
  - ú e$^-$e$^-$
  - ú eg/gg interakce
  - ú GigaZ
- § Prahová produkce SM Higgse

σ[e$^+$e$^-$ à ZH] ~ √ [s– (m$_H$ + m$_Z$)^2]

Možnost stanovit spin H (20 fb^{-1})

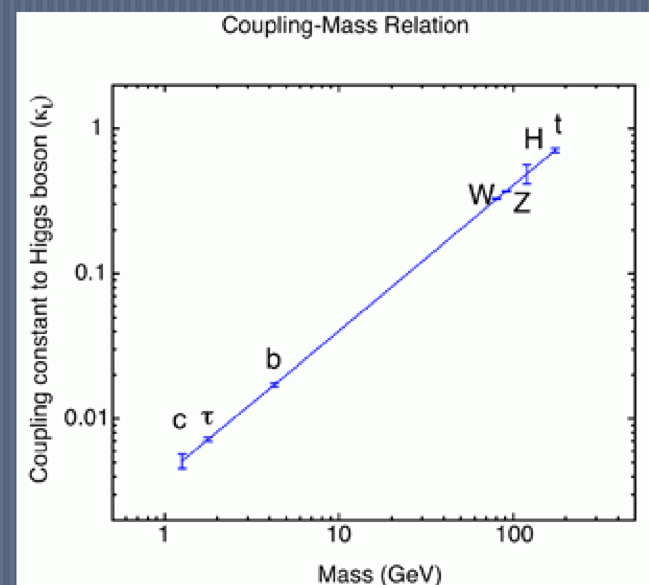


Vylučuje:
J^P=0$^-$,1$^-$,2$^-$,3$^\pm$,…
J^P= 1$^+$,2$^+$

- § Vazbová konstanta - SM částice p

$$k(\mathrm{Hpp}) = \sqrt{2\sqrt{2}G_F}\, m_p$$

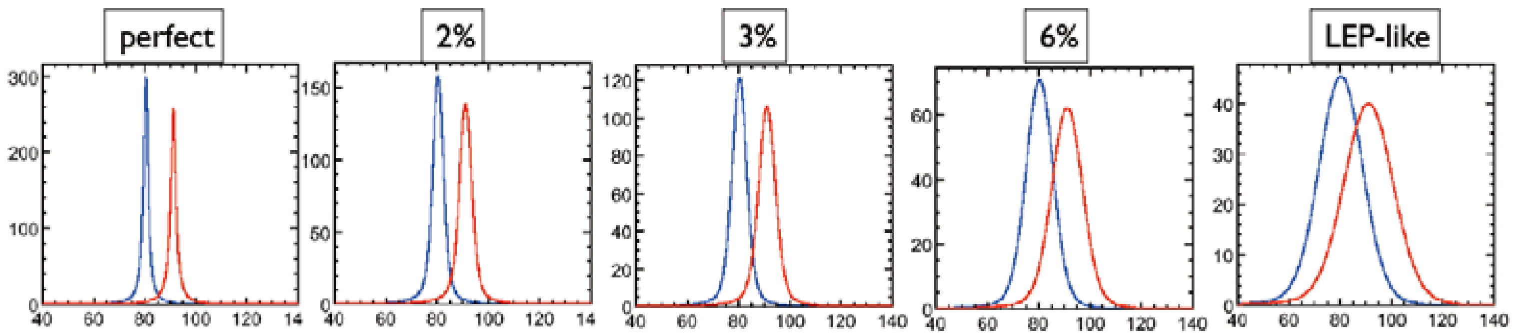
- § Higgs strahlung: e$^+$e$^-$ à ZH
- § WW fusion: e$^+$e$^-$ à nnH
- v Účinné průřezy pro produkci
- v Rozpadové větvící poměry
- v
- §



Energy measurement at ILC

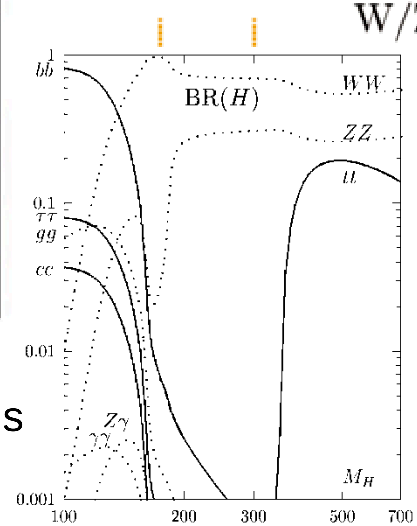
Mass Resolution: Requirements for separation

- Width of gauge bosons sets a natural scale for the required resolution

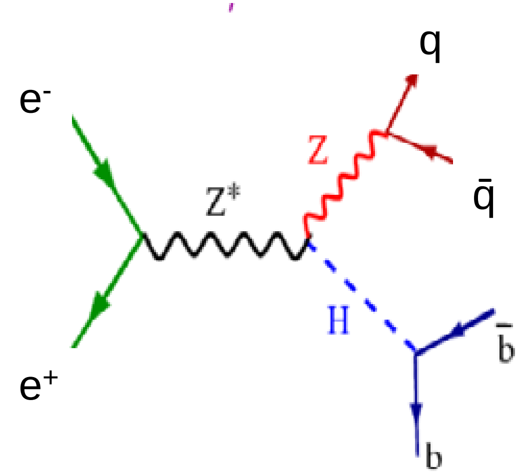


Jet E res.	W/Z sep
perfect	3.1 σ
2%	2.9 σ
3%	2.6 σ
4%	2.3 σ
5%	2.0 σ
10%	1.1 σ

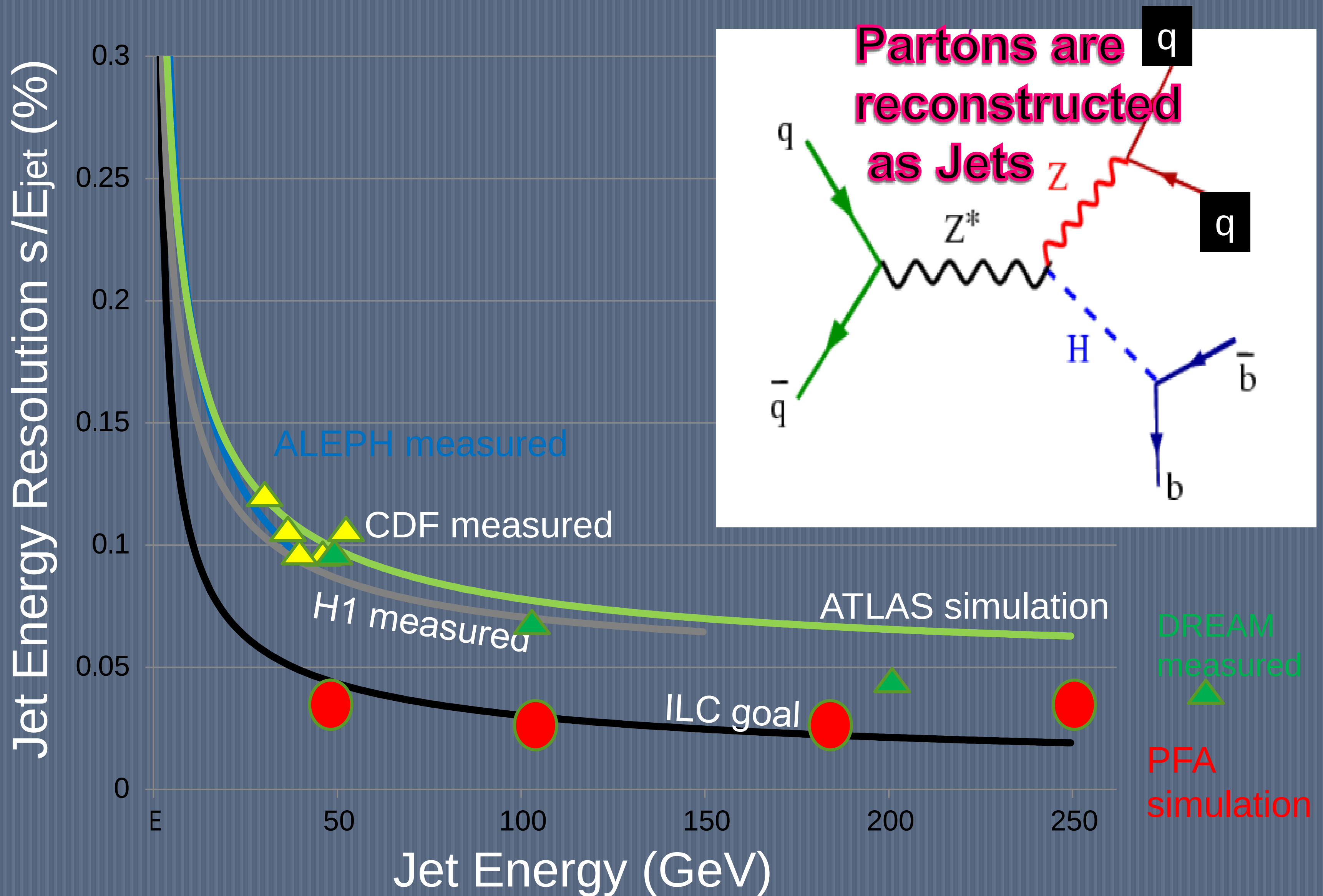
$$\mathrm{W/Z\ separation} = (m_Z - m_W)/\sigma_m$$



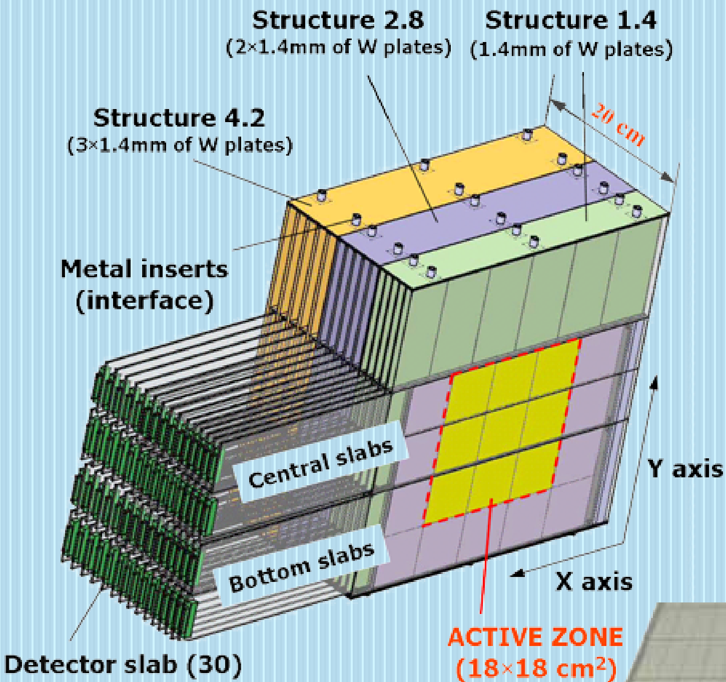
Branching ratios of SM Higgs

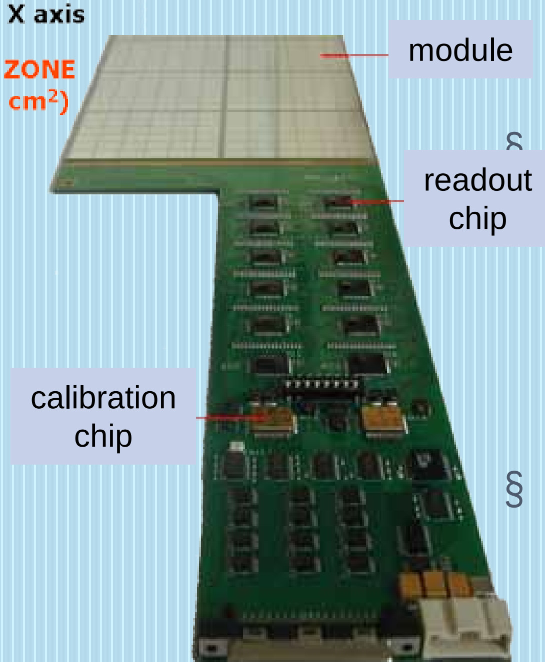


Jet energy resolution



Silicon-Tungsten ECAL

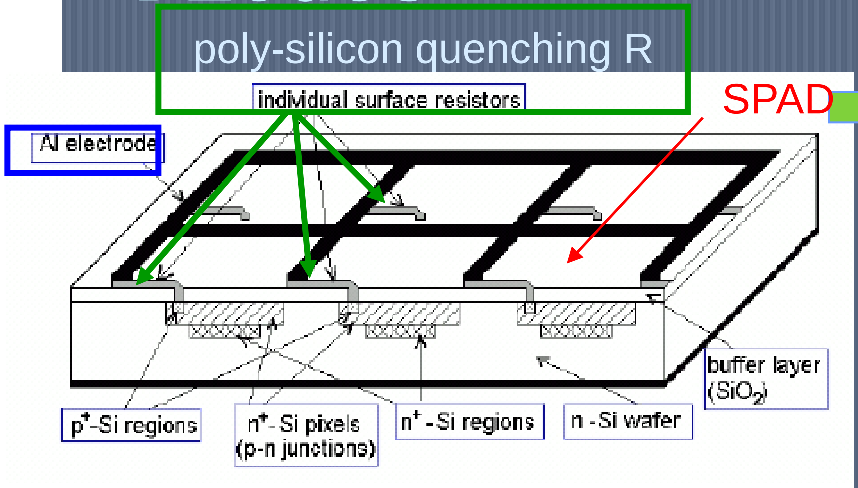




- Absorber
  - 30 layers of W: 1.4, (0.4 X_0), 2.8 and 4.2 mm thick
  - 24 X_0 in total
- Active Element
  - 30 layers of Si diode pads
    - 1 cm^2, 525 µm thickness
    - 6480 channels
  - ~ ½ sensors from Czech Rep. – Prague main contribution
- Read-out by ASIC
  - Large dynamic range
  - Auto-trigger on ½ MIP
  - On chip zero suppress
  - Ultra-low power « 25 µW/ch
- In beam 2006 - 8

2008 JINST **3** P08001

Array of Single Photon Avalanche Diodes



I will refer to one SPAD as pixel in the following

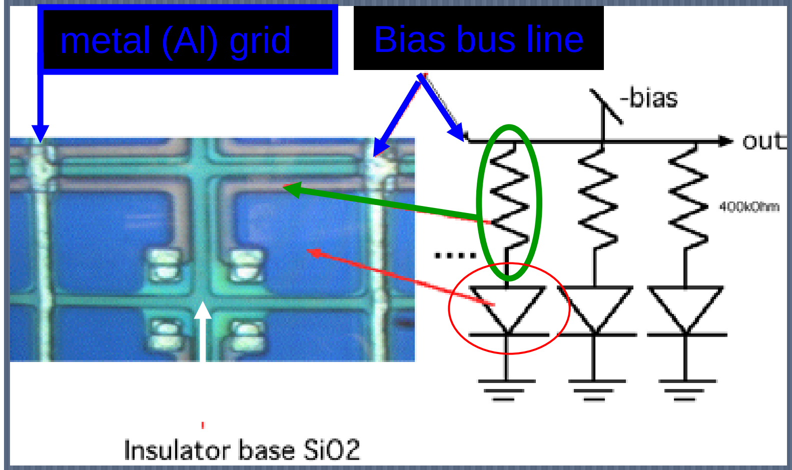
è typically 100-1000 pixels / mm²

Some typical pixel parameter:

-pixel size ~20-30 mm

-pixel capacitance C_{pixel} ~ 50 fmF

-quenching resistor R_{pixel} ~ 1-10 MW



all pixels connected in parallel

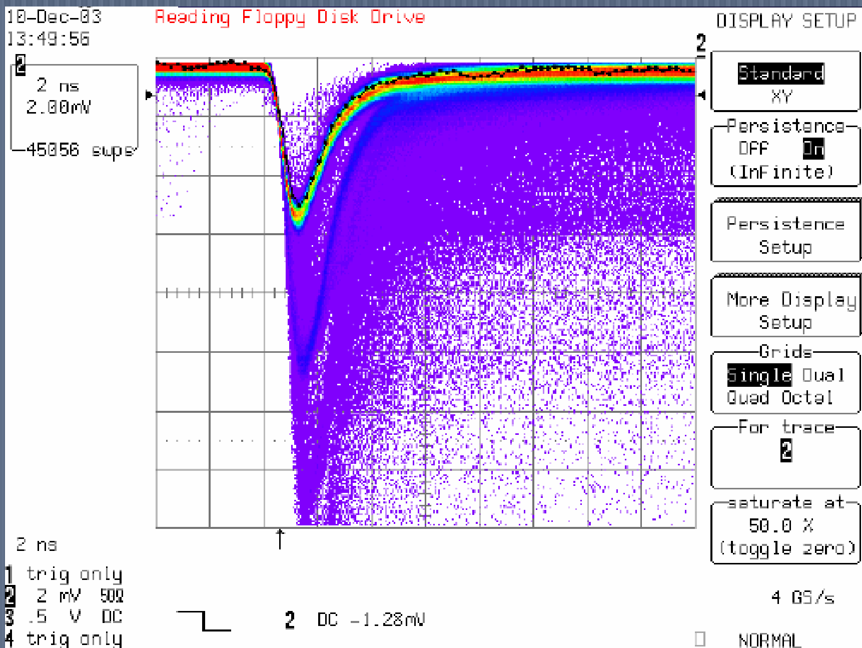
only one signal line

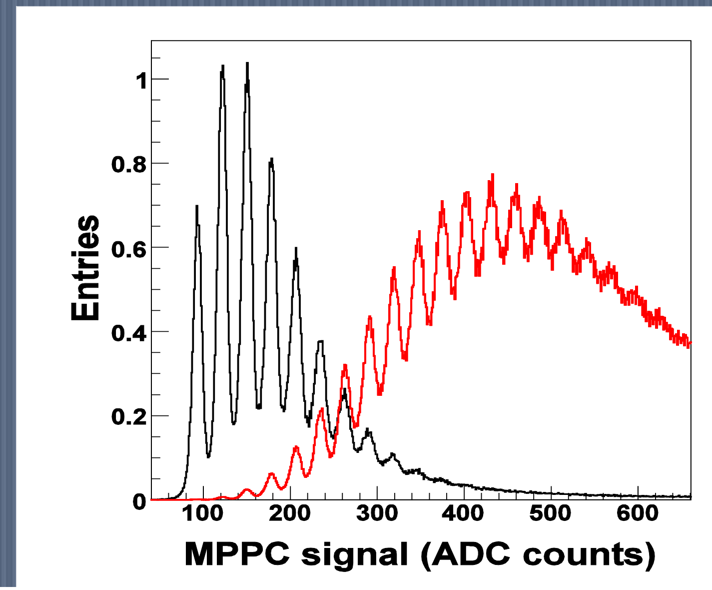
è output = Σ pixel signals

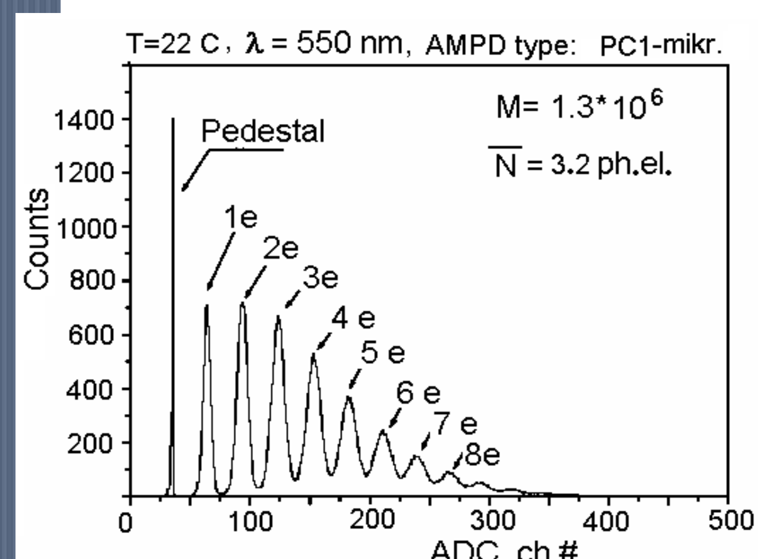
typical Bias voltage ~ 2 V above breakdown

SiPM properties: single pixel resolution

SiPM output is the analog sum of all pixel signals







high gain è pixel signal visible on scope

- signal rise time < 1 ns
- fast fall ~ 5-10 ns

recovery time tunable by choice of quenching R

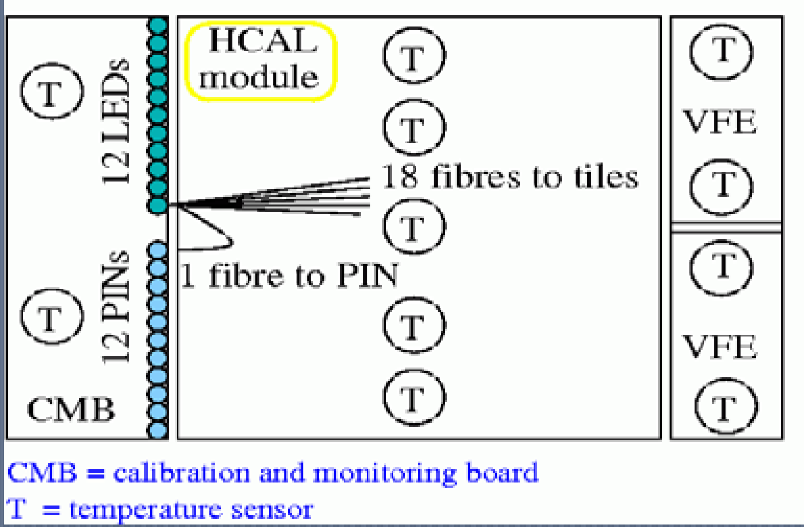
t ~ $R_{pixel}C_{pixel}$ ~ 20 – 500 ns

AMPD tested in LNP JINR and PSI

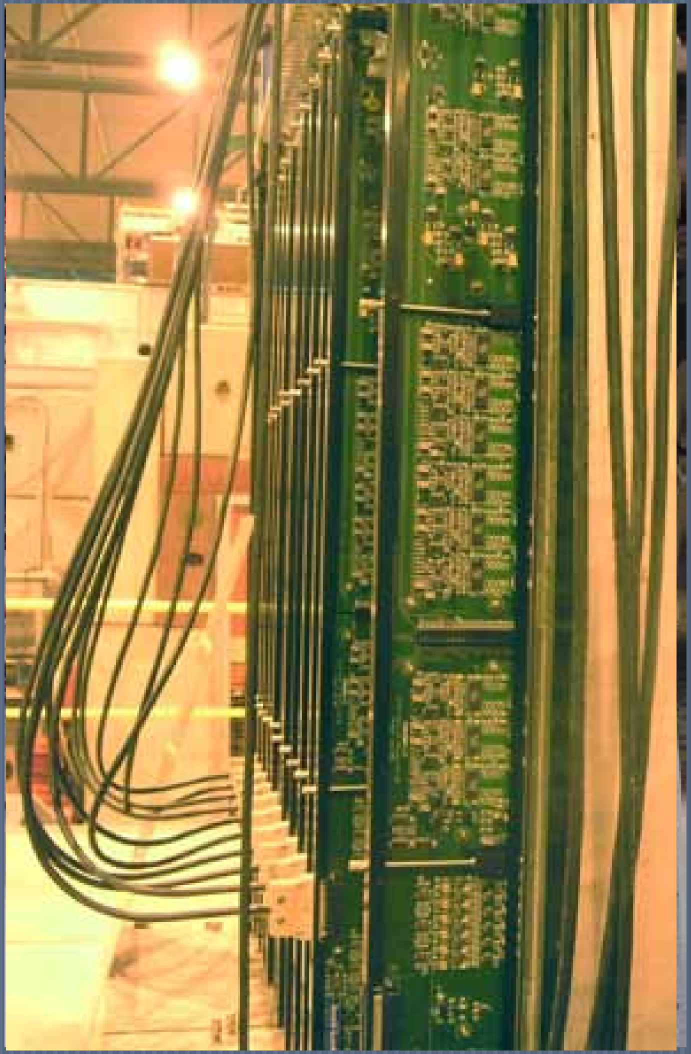
Calibration and monitoring system

Functionalities of the LED system:
1) gain calibration at low intensity light
2) provide reference pulses monitored by PIN diodes
3) provide full dynamic range for checking the SiPM response function

Temperature monitored by temperature sensors



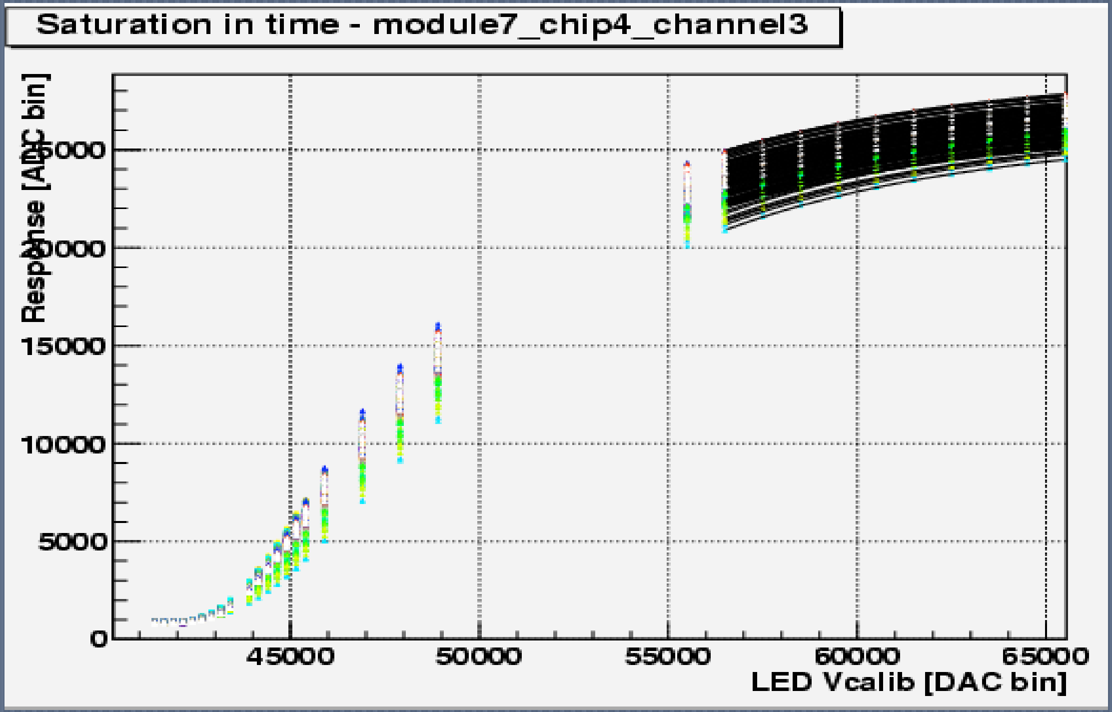
$$\frac{\Delta G/G}{\Delta T} \sim -1.7\%/K$$



Performance & Stability

N[ADC]

Fits: one channel, all runs



Example:
144 fits (FNAL) for one channel

- for 'good' runs similar behavior

→ extract saturation factor N[ADC] for all channels
→ apply calibration to pixels & temperature corrections → N[pix]
→ consistent results for all runs? → averaged over all runs
→ unique curve for all channels?

Energy reconstruction by software compensation – global method

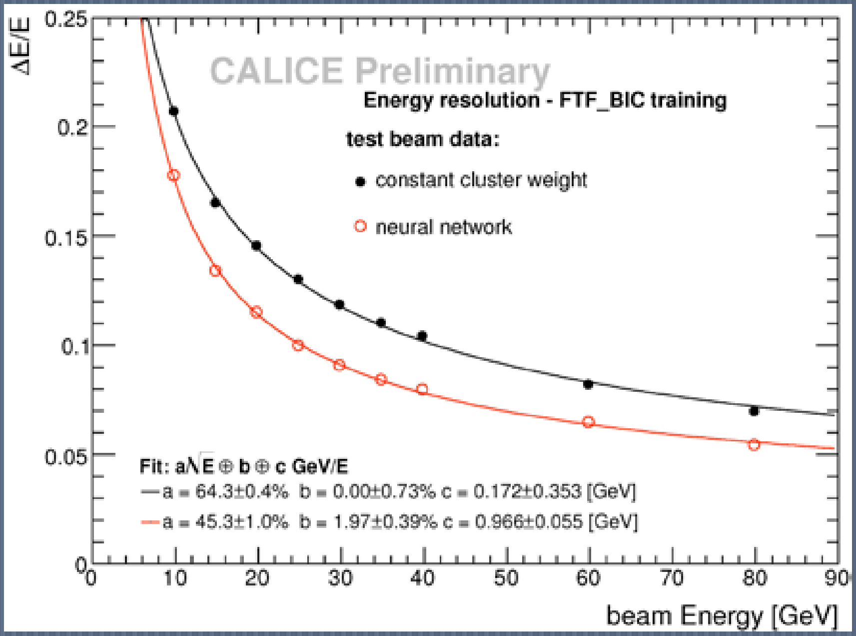
Cluster finding in HCAL to determine properties of the shower (global) (total energy, volume, longitudinal structure …)

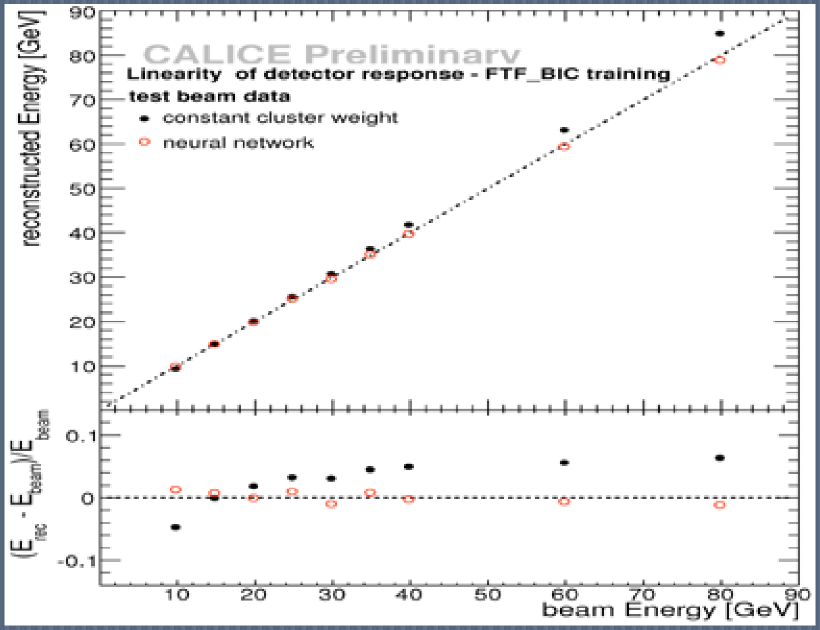
Used as input to neural net, training with the MC simulation

Resolution improved by ~ 25 %

Non-weighted distribution - larger response at higher energies.

Sw compensation – linearity back to ~ 2%

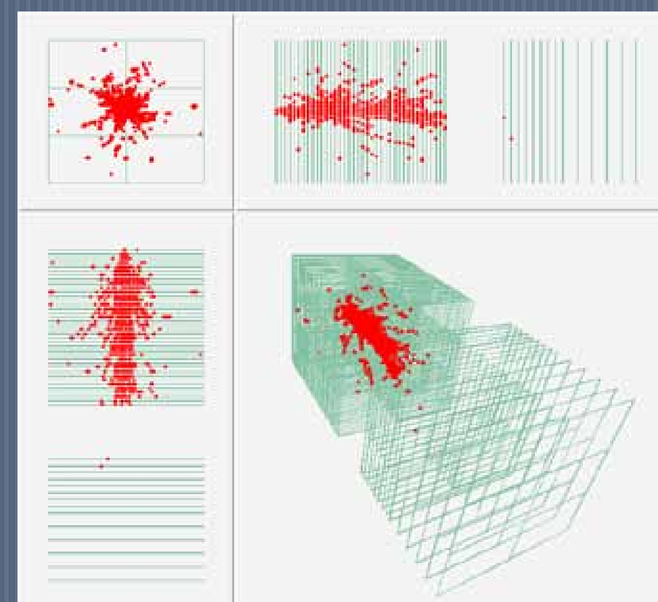


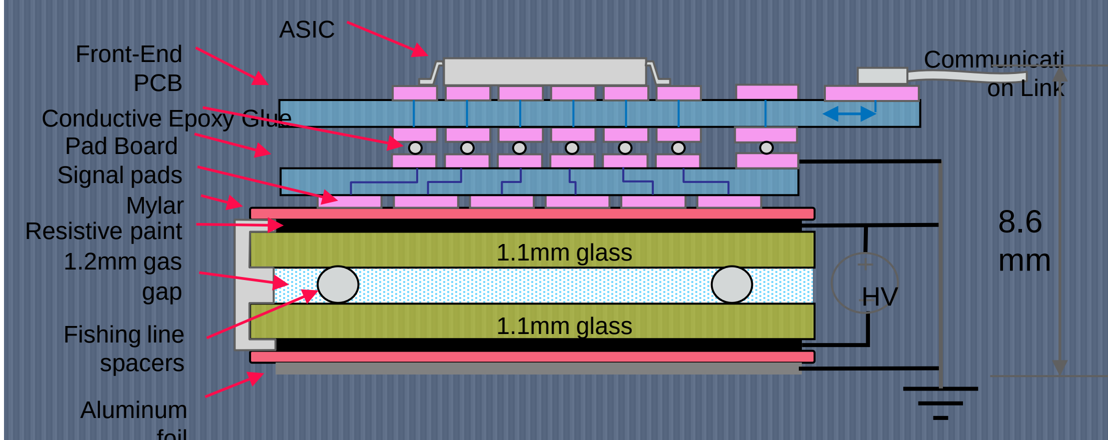


Digital calorimetry

finer shower imaging

- Digital readout: count particles in shower: gas detectors, silicon
- To prove the principle and compare the energy resolution to AHCAL
- Resistive Plate Chamber DHCAL: in test beam for ~ 1 year, data analysis ongoing





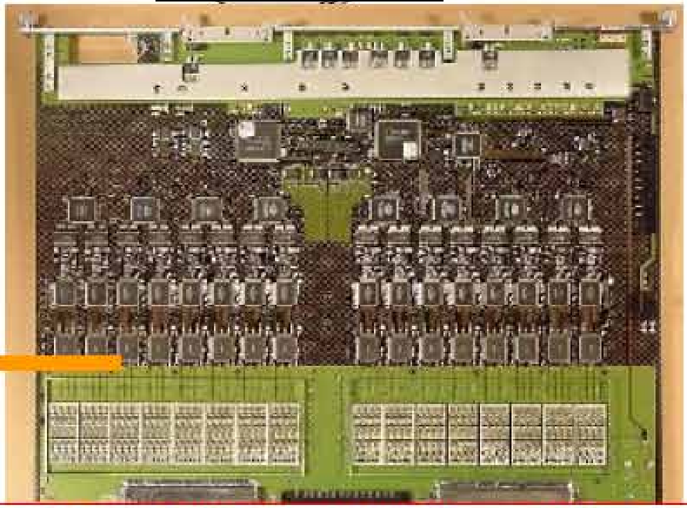
Integrated electronics

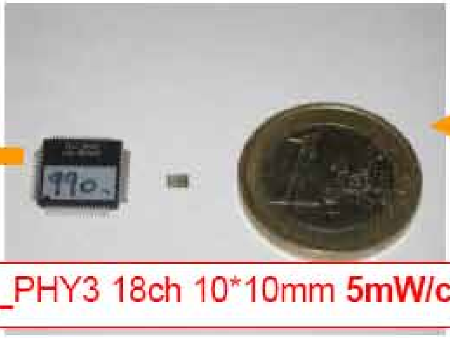
New era for chip design:

- Integration of analog and digital parts
- Large dynamic range (15 bits)
- Auto-trigger on ½ MIP (specific of ILC)
- On chip zero suppress
- Front-end embedded in detector è **Ultra-low power<<25µW/ch**
- 10^8 channels
- Compactness

- « Tracker electronics with calorimetric performance »
- No chip = no detector !!

[redacted]



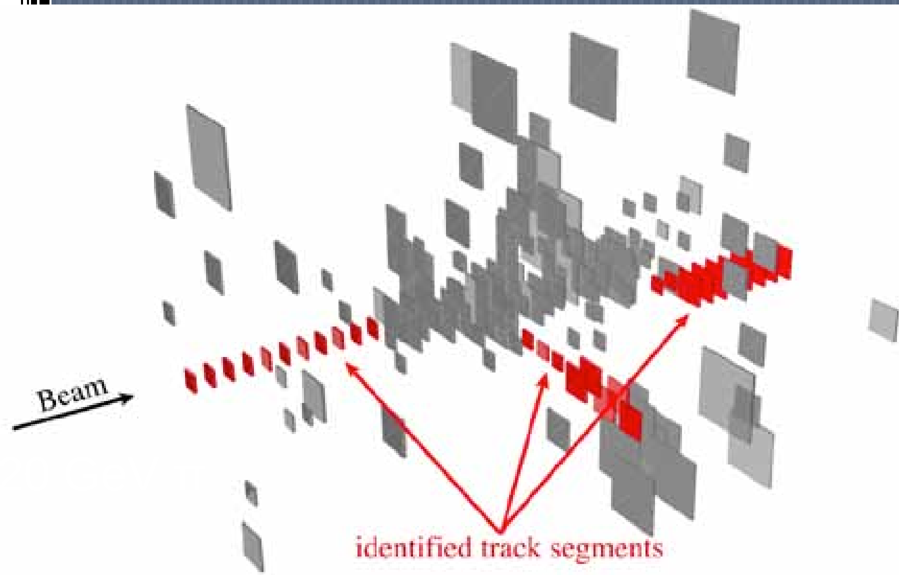


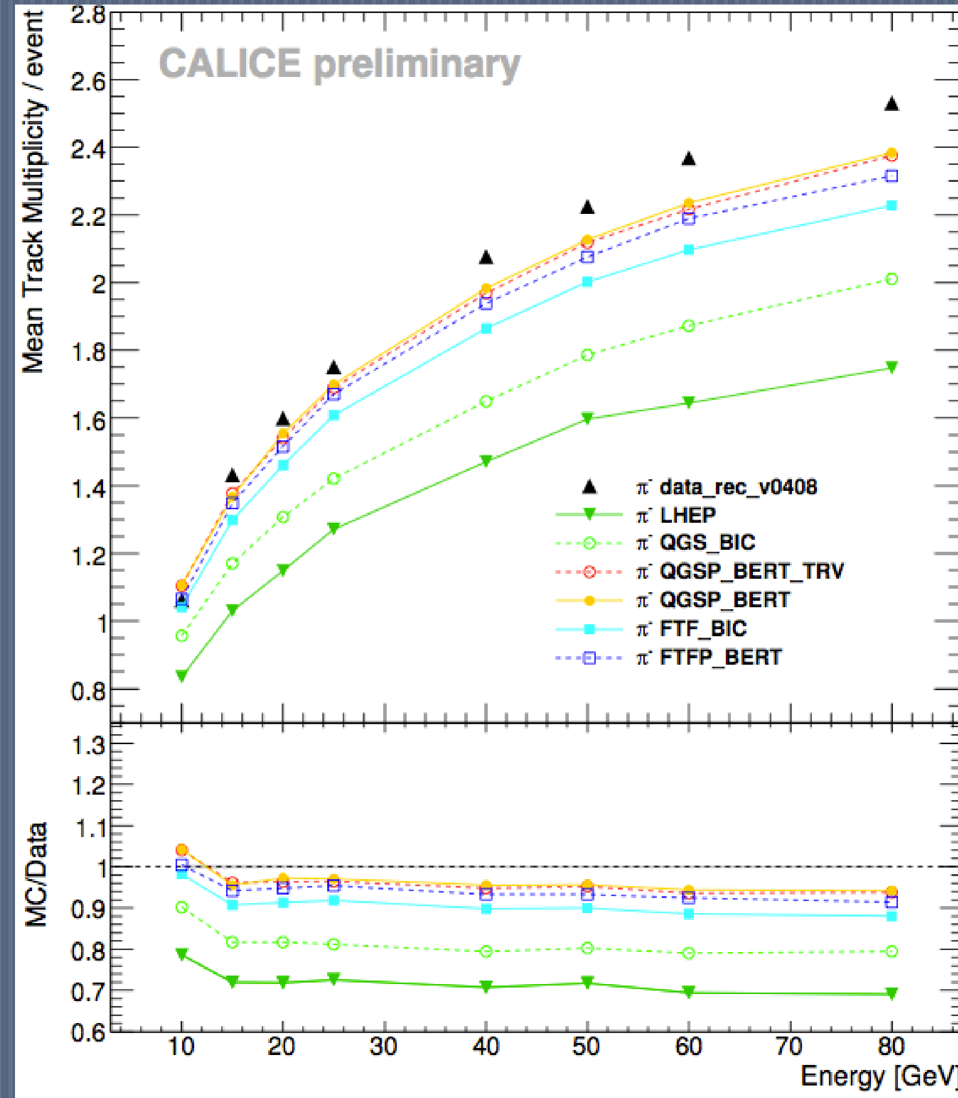
ILC : **25µW/ch**

FLC_PHY3 18ch 10*10mm **5mW/ch**

ATLAS LAr FEB 128ch 400*500mm **1 W/ch**

Track multiplicity





High granularity allows to reconstruct isolated parts of secondary particles in the shower

- Number of track segments underestimated by all models
- Similar result obtained for the mean track length