# PION SHOWERS IN HIGHLY GRANULAR CALORIMETERS

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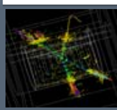
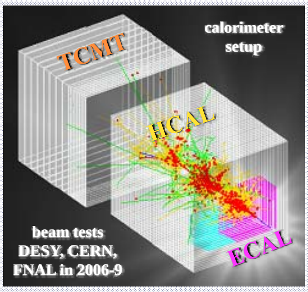
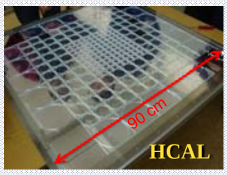


## THE CALICE EXPERIMENT




## ANALOG HADRON CALORIMETER AHCAL



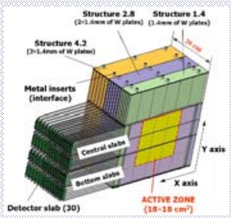

- 38 layers, 2 cm Fe absorbers + 5 mm scintillator thick tiles, 5.3 $\lambda_I$
- 7608 photodetectors SiPM
- A layer = 216 scintillator tiles, 3x3, 6x6, 12x12 cm$^2$
- 1 m$^3$ volume


Tile equipped with:
- WLS fibre
- photodetector
- calibration fibre

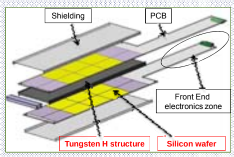
Photodetector:
- 1156 pixels in Geiger mode
- Gain ~ $10^5$-$10^6$

CALICE Collaboration, 2010 JINST **5** P05004

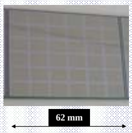
## Si/W ELECTROMAGNETIC CALORIMETER ECAL




- 30 layers of tungsten
- 24 $X_0$ total, 1 $\lambda_I$
- ½ integrated in detector housing
- compact and self-supporting detector
- 9720 channels in total




6x6 PIN diode matrix
- Resistivity 5kΩcm
- 80 (e/hole pairs)/μm
- Thickness 525 μm




Energy response linear to < 1%
Energy resolution $\sigma_E/E = 16.5\%/\sqrt{E} \oplus 1.1$

CALICE Collaboration, 2008 JINST **3** P08001

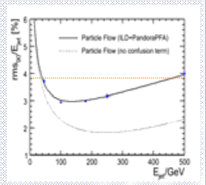
## PERFORMANCE REQUIREMENTS AT e$^+$e$^-$ COLLIDERS

- Jet energy resolution improvement by a factor ~2 with respect to LEP
- Separation of $Z^0$, W hadronic decays, multijet final states
- Better spatial single particle separation

## PARTICLE FLOW EVENT RECONSTRUCTION (PFA)

- Combination of effective reconstruction in the tracker with separation of charged and neutral clusters in calorimeters
- Requires high calorimeter segmentation
- Reconstruction package = PandoraPFA

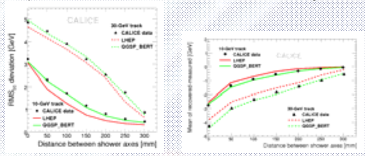
## RESULTS



MC studies for ILD:
- detector meets this requirement for 40-400 GeV jets
- Benchmarked using $Z^0$ hadronic decays

M.A.Thomson, NIM **A611** (2009) 25

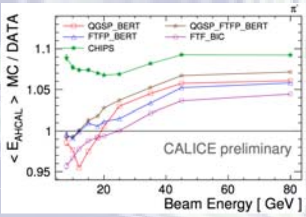
CALICE test beam data, PandoraPFA reconstruction, MC comparison
- Crucial test for PFA performance
- Two test beam showers superimposed, one of them considered as a neutral cluster
- Difference between recovered and measured energy is the most sensitive characteristics
- Two different MC physics models used for comparison
- The agreement between data and MC confirms the previous results based on simulation only



CALICE Collaboration, 2011 JINST **6** P07005

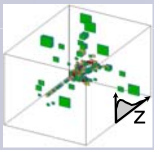
## π SHOWER PROPERTIES: DATA / GEANT4 PHYSICS LIST I

❖ Test beam data taken in 2007-9 at CERN and FNAL in the energy range 8-80 GeV
❖ Data vs MC comparison for different Geant4 physics lists, version 9.3:
- QGSP_BERT → Bertini cascade at low E → LEP (GHEISHA) →QGSP at 10-25 GeV
- FTFP_BERT, FTF_BIC → Bertini cascade (BIC) model at low E → Fritioff string model at 4-5 GeV
- QGSP_FTFP_BERT → Bertini cascade at low E → FTFP → QGSP
- CHIPS → Experimental, no model transition, in development

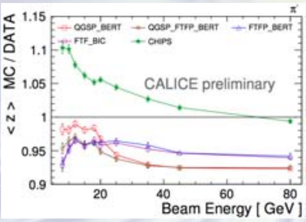



Visible energy in HCAL as a function of $E_{beam}$

### LONGITUDINAL SHOWER IN PROFILE IN HCAL



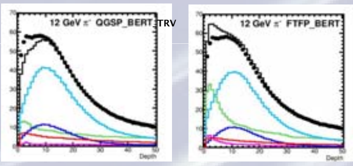
- high granularity improves reconstruction of shower starting point
- underestimated by most of models
- CHIPS model overestimates
- sensitive to the shape of electromagnetic part in the hadron shower




Longitudinal shower centre as a function of $E_{beam}$

### LONGITUDINAL SHOWER PROFILE IN ECAL

CALICE Collaboration, 2010 JINST **6** P07005

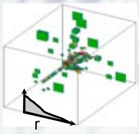



Shower composition:
- electrons/positrons knock-on, ionisation
- protons from nuclear fragment.
- mesons
- others
- sum
- data

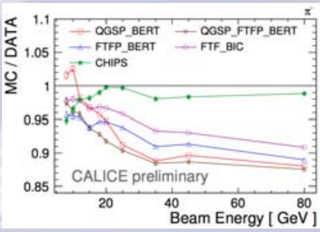
- Significant difference between models, especially for protons (short range component).
- Granularity allows to disentangle contributions

## π SHOWER PROPERTIES: DATA / GEANT4 PHYSICS LIST II

### LATERAL SHOWER IN PROFILE IN HCAL

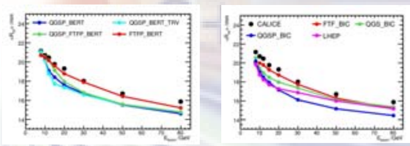


- lateral shower profile critical for PFA performance
- underestimated by most models
- best described by CHIPS model
- sensitive to the shape of electromagnetic part in the hadron shower

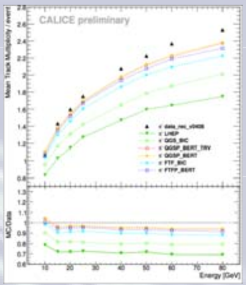



Transverse shower centre as a function of $E_{beam}$

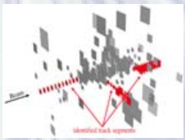
### LATERAL SHOWER PROFILE IN ECAL



- Small energy favours 'BERT' models
- Towards high energy: underestimation of content in SiW ECAL
- Relatively small difference between models (~15%)




### SHOWER SUBSTRUCTURE: TRACK SEGMENTS



- MIP-like track segment in event
- Mean track multiplicity underestimated by all models
- Best agreement with QGSP-BERT, QGSP_BERT_TRV and FTP_BERT
- MIP-like tracks can be used for calibration

## CONCLUSIONS

- Calorimeter prototypes with high granularity were built and successfully tested in beams
- Imaging calorimetry allows for the validation of hadronic shower simulations at an unprecedented level of details
- FTF based models agree with data within 5-10% and show the best overall performance (8 - 80 GeV)
- QGSP_BERT physics list gives better description of test beam data than LHEP
- The agreement between PandoraPFA reconstruction of real test beam data and MC simulation demonstrates the reliability of MC simulation done for the full size detector (CALICE Coll., 2011 JINST **6** P07005)
- AHCAL and SiW ECAL are building new prototypes evaluating technical solutions for the final detector: optimised granularity, realistic dimensions, integrated front-end electronics, small power consumption

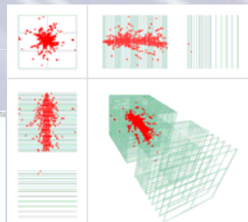
## DIGITAL CALORIMETRY: even more finer shower imaging

- Digital readout: count particles in shower: gas detectors, silicon
- To prove the principle and compare the energy resolution to AHCAL
- Current status:
  - RPC DHCAL: has been in test beam for ~ 1 year, data analysis started
  - RPC sDHCAL: test beam this summer, 1st physics data expected this fall
  - Micromegas, GEM based (s)DHCAL: single chamber level, first beam tests are already done

RPC-Fe DHCAL

RPC-Fe semiDHCAL

Shower in sDHCAL



120 GeV proton in DHCAL ~ 1400 hits

- RPCs: readout of 1x1 cm$^2$ pads on 1 m$^2$ area with a resolution of 1 or 2 bits
- Both DHCALs worked amazingly well in test beams at FNAL and CERN