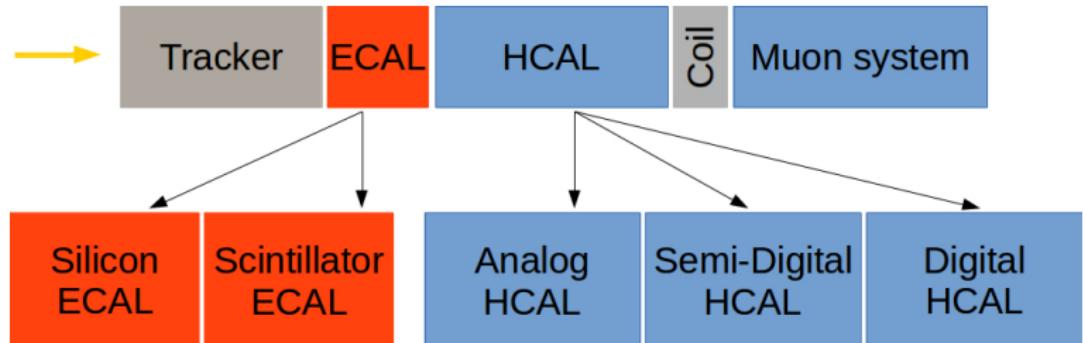


# Shower characteristics of particles with momenta up to 150 GeV in CALICE tungsten calorimeters

Eva Sicking (CERN / LAPP, IN2P3)  
for the CALICE collaboration

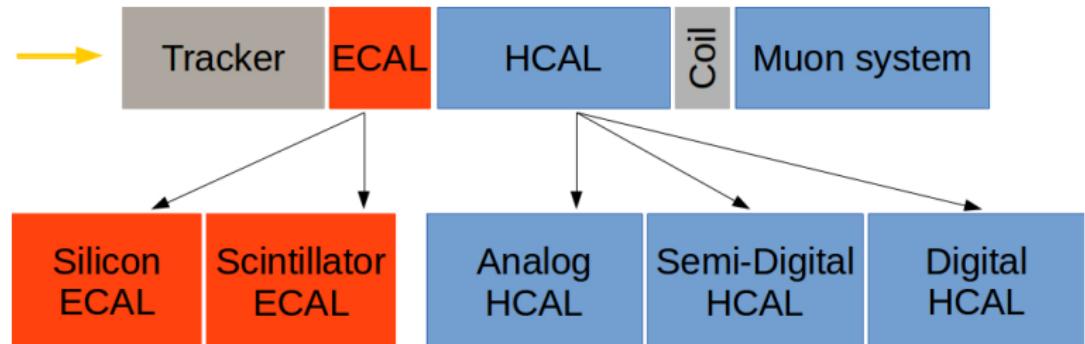
Vienna Conference of Instrumentation  
17 Februaray 2016

# CALICE prototypes of highly granular calorimeters



Readout	Silicon PIN diodes	Scint. strips+ Silicon Photo Multipliers	Scint. tiles+ Silicon Photo Multipliers	RPCs (μMegas)	RPCs (GEMs)
Granularity (mm <sup>3</sup> )	10 × 10 × 0.5	45 × 5 × 3	30 × 30 × 5	10 × 10 × 1.2	10 × 10 × 1.15
Absorber	W	W	Fe or W	Fe	Fe or W
Layer × thickness (mm)	10×1.4+ 10×2.8+ 10×4.2	30×3.5	Fe: 38×21.4 W: 38×10	48×20	Fe: 38×20 W: 39×10

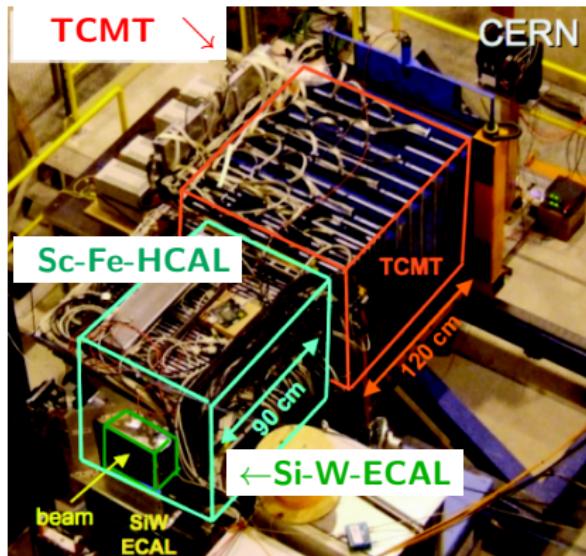
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Absorber	W	W	Fe or W	Fe	Fe or W
Layer × thickness (mm)	$10 \times 1.4 +$ $10 \times 2.8 +$ $10 \times 4.2$	$30 \times 3.5$	Fe: $38 \times 21.4$ W: $38 \times 10$	$48 \times 20$	Fe: $38 \times 20$ W: $39 \times 10$
<b>Si-W-ECAL</b>		<b>W-AHCAL</b>			

# CALICE test beam experiments

- Test beam experiments in 2006–2015 at DESY, CERN, FNAL
- Prototypes of up to  $\sim 1\text{ m}^3$ ,  $\sim 2\text{ m}^3$  including Tail Catcher Muon Tracker



Sc-HCAL:  $\sim 8\,000$  readout channels

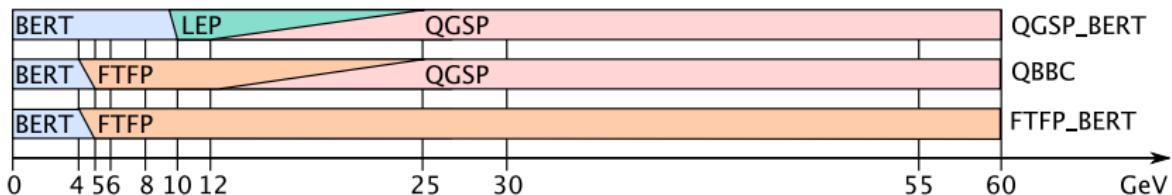


RPC-HCAL:  $\sim 500\,000$  readout channels

→ Validation of new calorimeter technologies as well as Geant4 simulation

# Geant4 Physics Lists

- Hadronic interactions in Geant4 based on phenomenological models
  - String parton models: QGS(P), FTF(P)
  - Parametrised models: LEP, HEP
  - Cascade models: BERT, BIC
  - Precompound model
- Models are combined in “physics lists”



- Model extension HP
  - Data driven **High Precision** neutron package
  - Assumed to be important for neutron rich absorbers

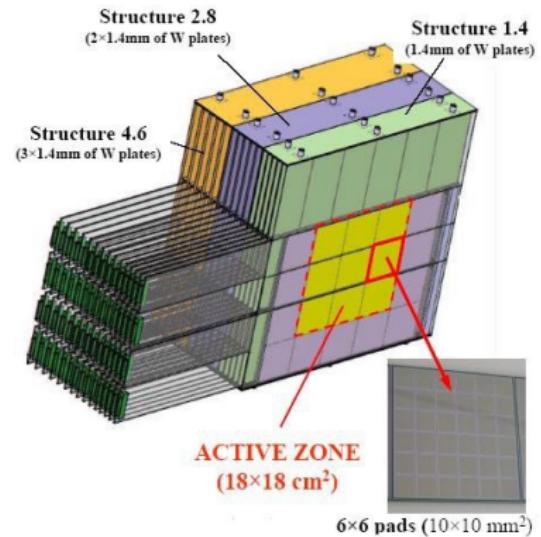


## Si-W-ECAL test beam analysis



# CALICE silicon-tungsten ECAL

- Absorber: tungsten plates of 1.4–4.2 mm
- Active material: silicon PIN diodes of 525  $\mu\text{m}$  thickness
- Granularity:  $10 \times 10 \text{ mm}^2$

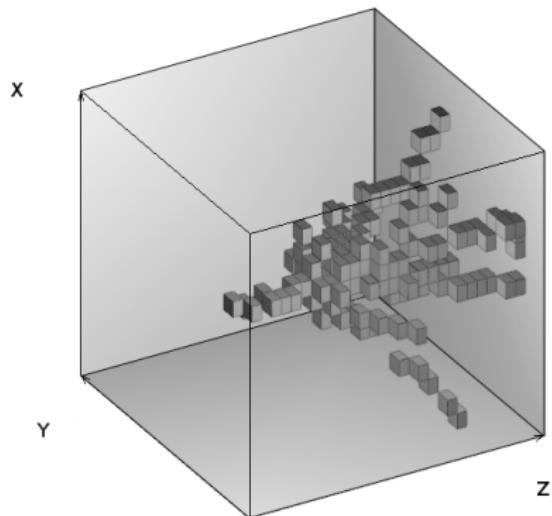


- 3 modules of each 10 layers with increasing W thickness
- Total depth  $\doteq 24 X_0$ ,  $1 \lambda_l$
- Active zone of  $18 \times 18 \text{ cm}^2$

# Test beam experiments at FNAL in 2008

- Test beam data recorded at FNAL in 2008 of  $\pi^-$  at 2 GeV–10 GeV
- $\sim 60\%$  of hadrons interact in Si-W-ECAL of  $1 \lambda_l$
- Detection efficiency 60%–93%
- Highly granular ECAL → detailed view of the primary interactions of hadrons
- Comparison to **Geant4 v9.6 p01**
- Study interactions in terms of shower observables: radial and longitudinal distributions  
▶ **NIM A794 2015 240**
- New: Study energy fraction in interaction region  $f_{IR}$  and number of secondary tracks  $N_{\text{tracks}}$   
▶ **CALICE Analysis Note 055**

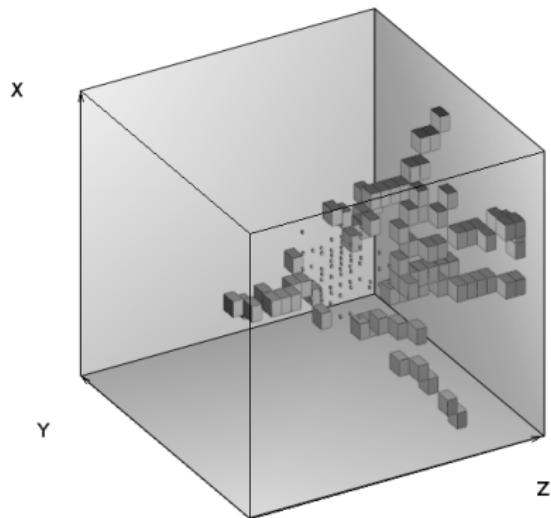
$\pi^-$  @ 10 GeV (FTFP\_BERT)



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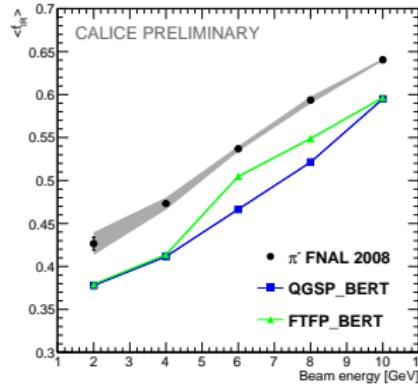
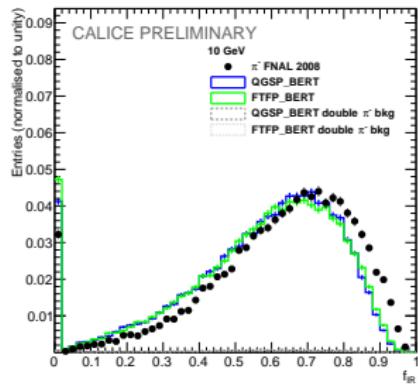
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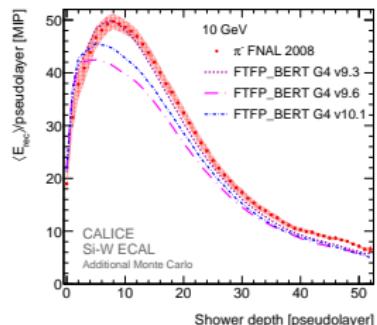
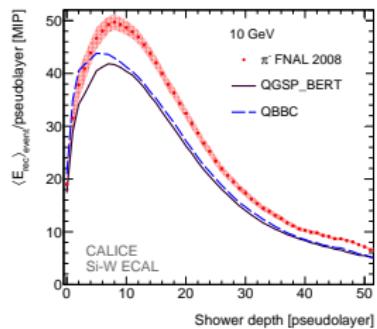
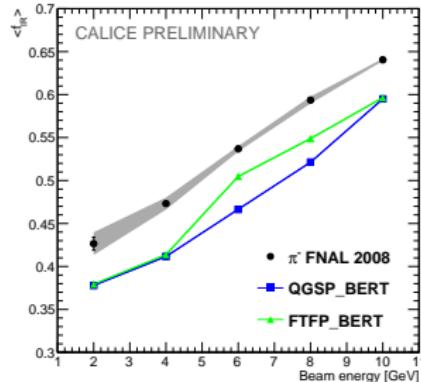
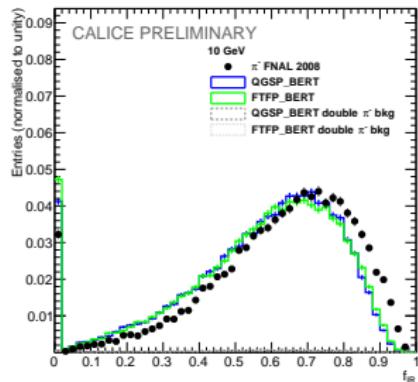
- **Interaction region:** all hits with at least six neighbouring pads with signal

# Energy fraction in interaction region $f_{IR}$



- Fraction of the energy deposited in the interaction region increases with beam energy
- $f_{IR}$  is underestimated by Geant4 by up to 20%,  
**FTFP\_BERT** better than **QGSP\_BERT**

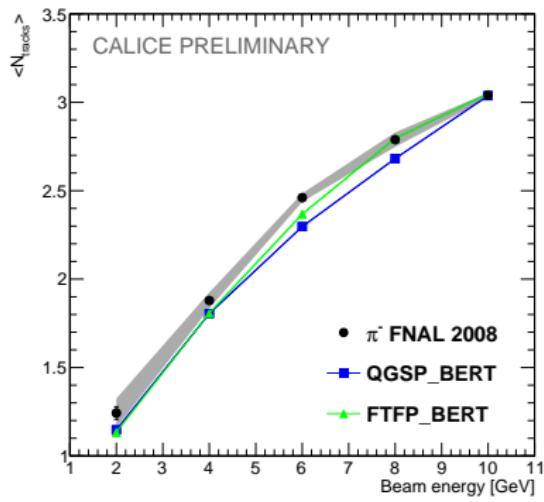
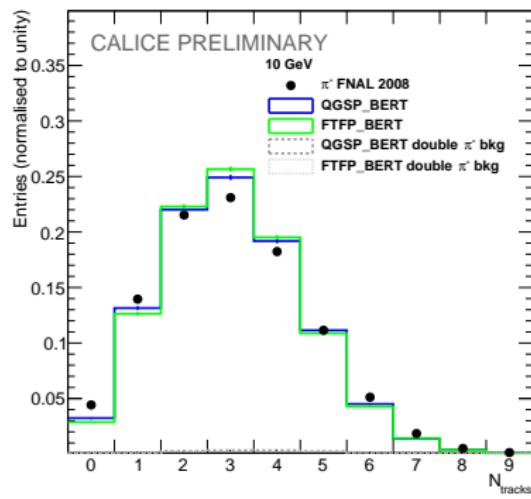
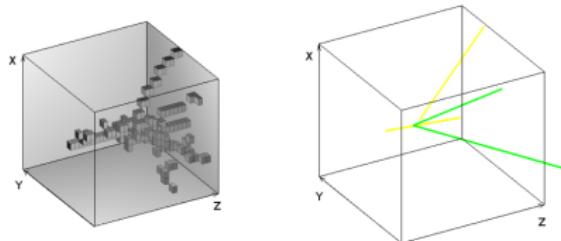
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- Fraction of the energy deposited in the interaction region increases with beam energy
- $f_{IR}$  is underestimated by Geant4 by up to 20%,  
**FTFP\_BERT** better than **QGSP\_BERT**
- Underestimation of energy in shower start also observed in longitudinal energy profile (for same Geant4 version)

# Number of secondary tracks

- Reconstruct tracks in hadron shower
- Number of reconstructed tracks within shower is well described by Geant4

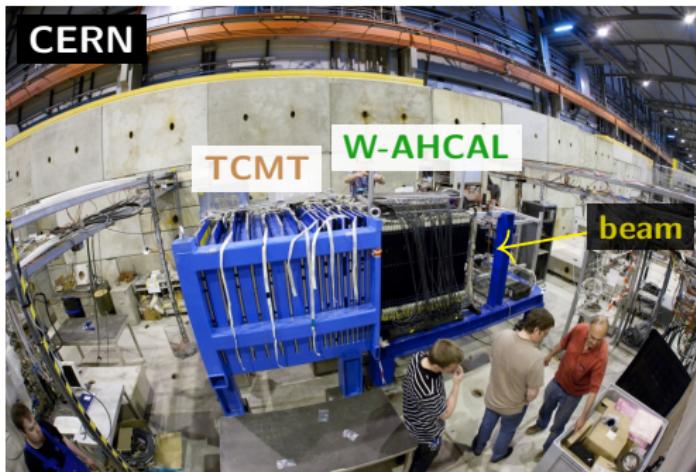


## W-AHCAL test beam analysis

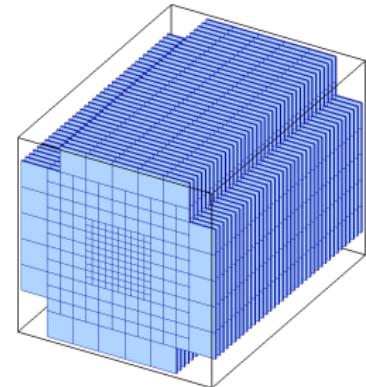
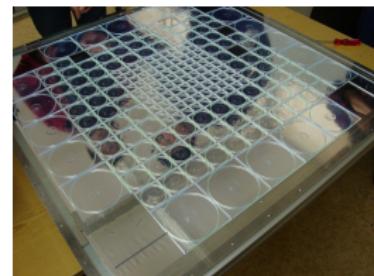


# CALICE scintillator-tungsten HCAL

- Dense tungsten absorber for large  $\sqrt{s}$  at CLIC
- Absorber: 1 cm thick tungsten plates
- Active material: 0.5 cm thick scintillator tiles
- Granularity:  $3 \times 3 \text{ cm}^2$  in central region,  
 $6 \times 6 \text{ cm}^2$  and  $12 \times 12 \text{ cm}^2$  in outer regions
- Readout: Silicon Photomultipliers (SiPM)



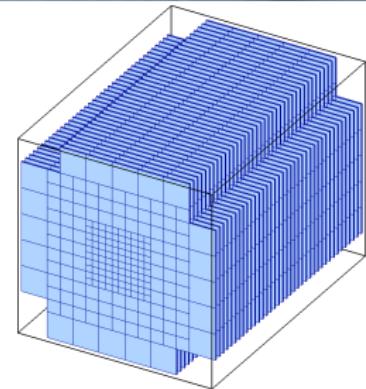
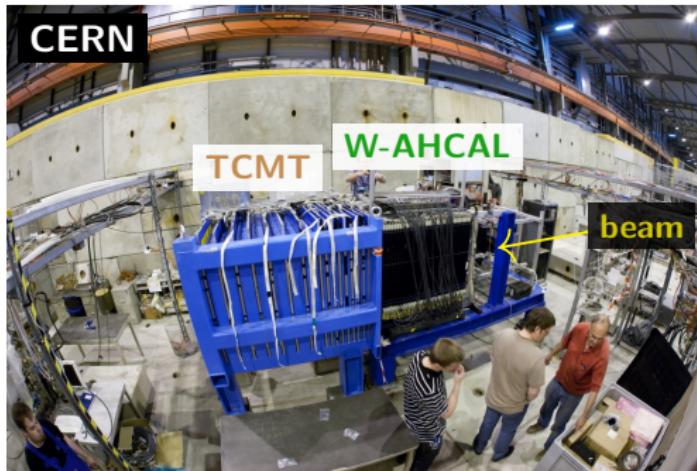
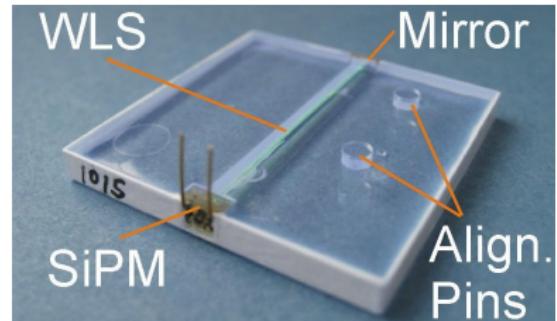
Sensitive layer of the Sc-HCAL



- Prototype of  $\sim 1 \text{ m}^3$  with 38 layers

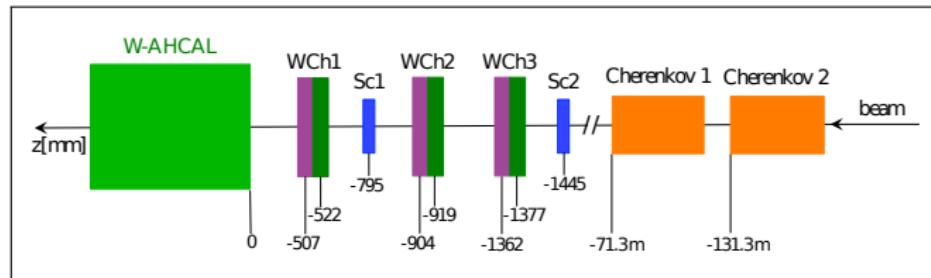
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# Test beam experiments at CERN SPS in 2011



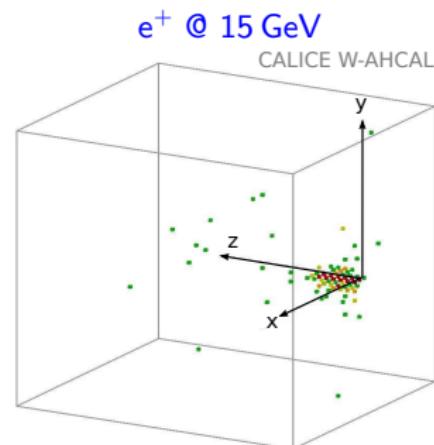
- **W-AHCAL** (38 layers  $\hat{=} 5 \lambda_l$ ,  $108 X_0$ )

- $15 \text{ GeV} \leq p_{\text{beam}} \leq 150 \text{ GeV}$

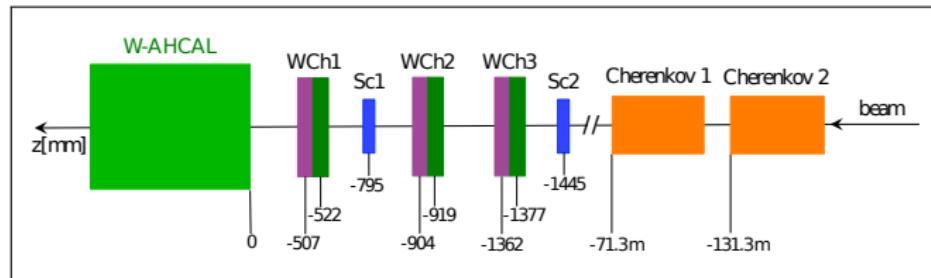
- $e^\pm$  beam/ mixed beam  $\mu^\pm, \pi^\pm, K^\pm, p$

- Focus of publication 2015 JINST 10 P12006

- Comparison between data and **Geant4 v9.6 p02** for W-AHCAL
- Validate Geant4 for sampling HCAL with W absorber for full hadron shower



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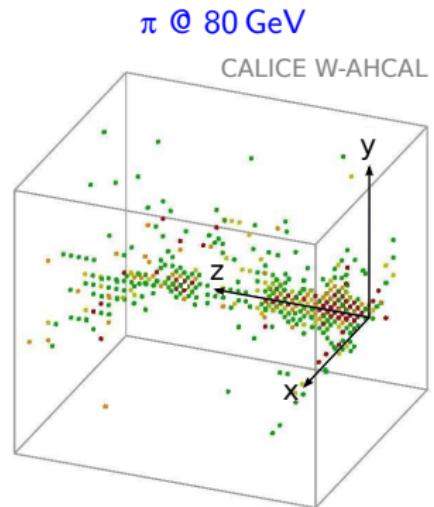
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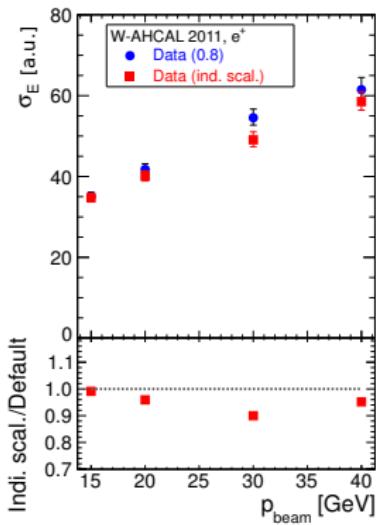
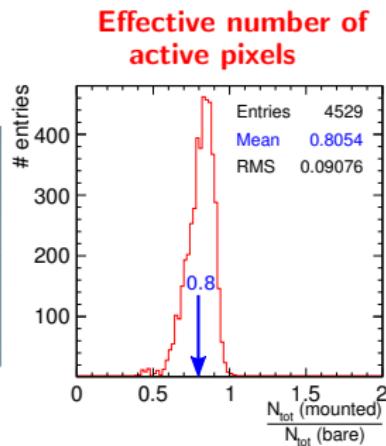
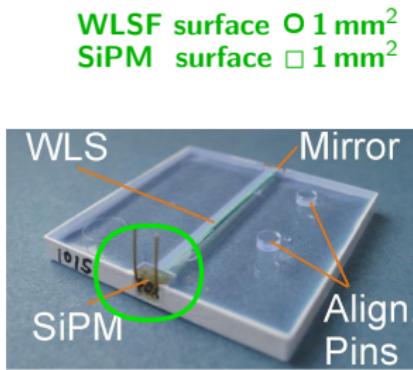
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# Alignment between WLSF and SiPM

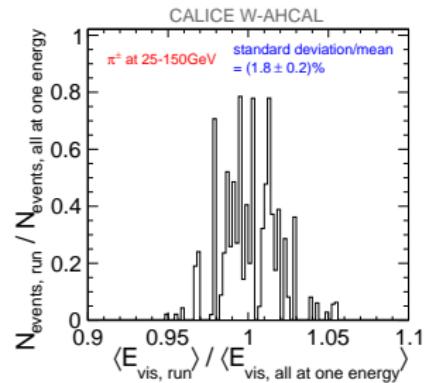
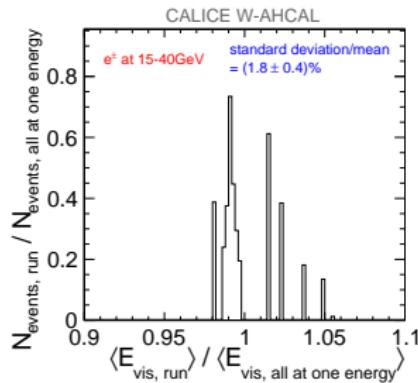
- Effective number of pixels for mounted SiPMs varies with SiPM-WLSF alignment
- Exact number plays important role in energy reconstruction at high cell energies



- Use **individual effective pixel numbers**, available for 60% of cells
- Improves energy resolution
  - Improves agreement between data and simulation for  $e^+$ , where only few cells contribute to energy sum

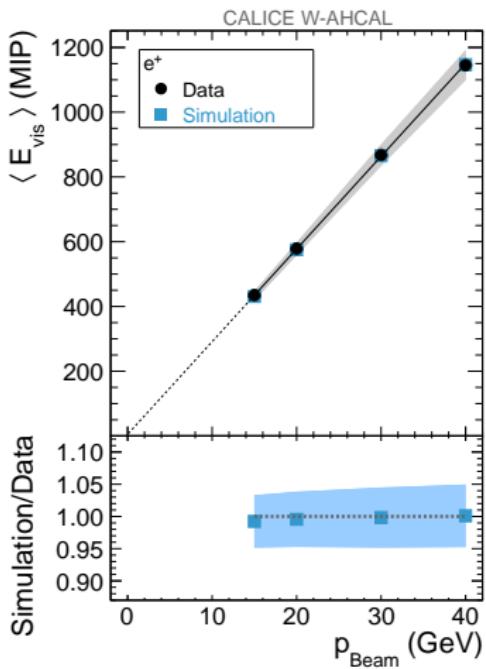
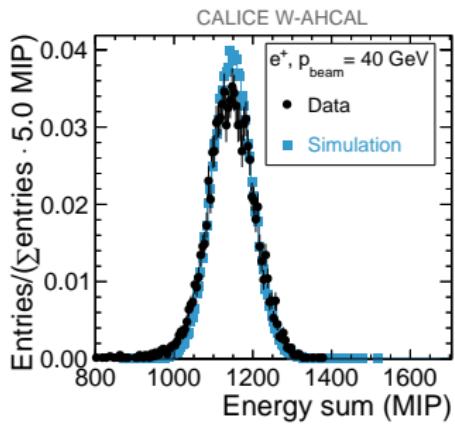
# Systematic uncertainties

- Comprehensive study of systematic uncertainties for all observables
- Example: **detector stability** over several data taking periods



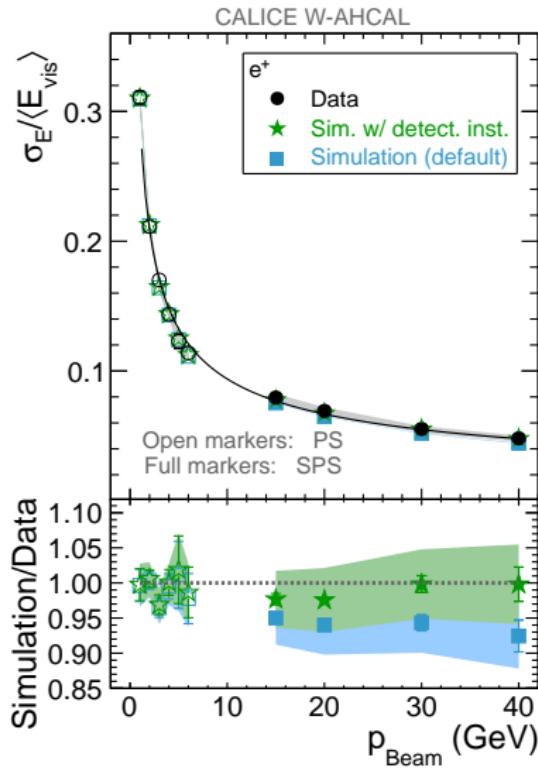
Source	— Systematic uncertainty on $\langle E_{\text{vis}} \rangle$ — for $e$ (%)      for $\pi, K$ , and protons (%)	Assigned to
SiPM saturation scaling	1.4–3.0	0.4–1.5 data
MIP constants	2.0	2.0 data
<b>Detector stability</b>	1.8	1.8 data
Shower start	-	0.1 data
Inter-tile cross-talk	2.7	2.7 MC

# Positron energy sum and linearity



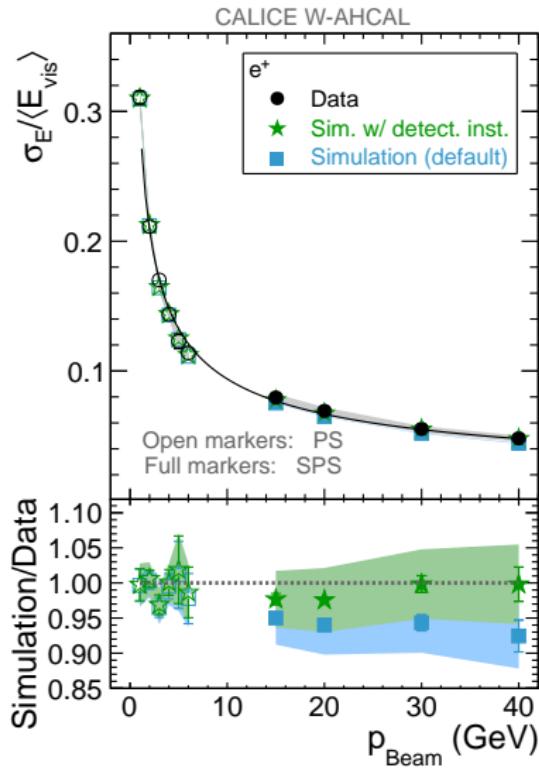
- Data and simulation agree well within systematic uncertainties
- Good agreement gives confidence in understanding of calibration and simulation implementation

# Positron resolution



- Implement detector instability measured in data into simulated energy resolution
- Data and MC with detector instability agree well within uncertainties
- Energy resolution well described by 
$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E[\text{GeV}]}} \oplus b \oplus \frac{c}{E[\text{GeV}]}$$
- Include PS data to better constrain the fit
- W-AHCAL PS+SPS:**  $\rightarrow 2.80 X_0$  per layer  
 $a_{\text{data}} = (29.5 \pm 0.4) \% \sqrt{\text{GeV}},$   
 $a_{\text{sim}} = (28.7 \pm 0.5) \% \sqrt{\text{GeV}}$
- W-AHCAL PS:**  
 $a_{\text{data}} = (29.6 \pm 0.5) \% \sqrt{\text{GeV}}$
- Fe-AHCAL:**  $\rightarrow 1.24 X_0$  per layer  
 $a_{\text{data}} = (21.5 \pm 1.4) \% \sqrt{\text{GeV}}$

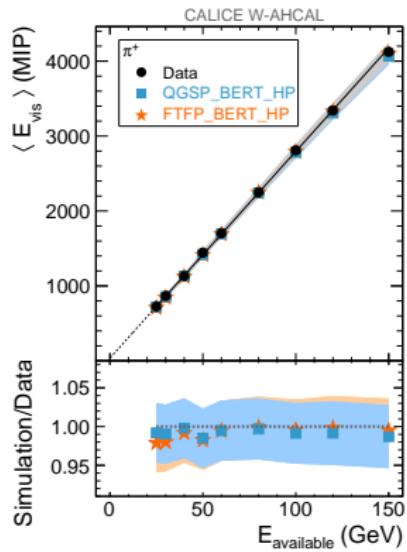
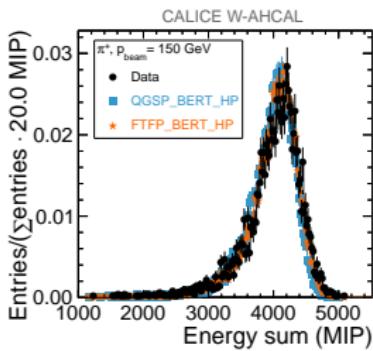
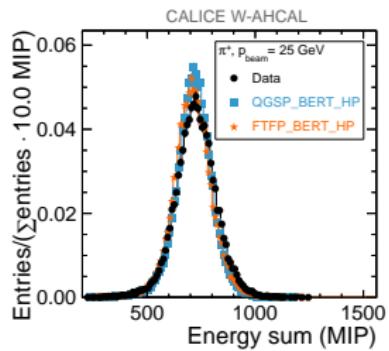
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 $a_{\text{data}} = (21.5 \pm 1.4) \% \sqrt{\text{GeV}}$
- **Expectation for el.-mag. energy resolution:**  

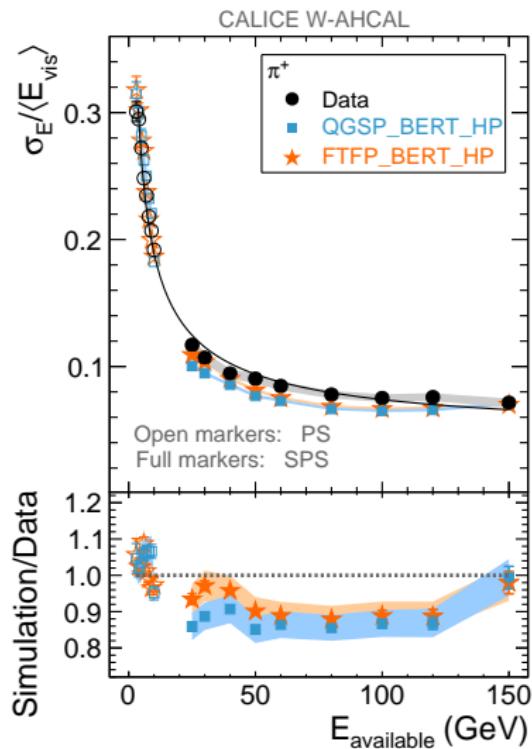
$$\frac{a_W}{a_{\text{Fe}}} = \sqrt{\frac{t_W}{t_{\text{Fe}}}}$$
 however  $1.35 \pm 0.09 \neq 1.5$

# Pion linearity



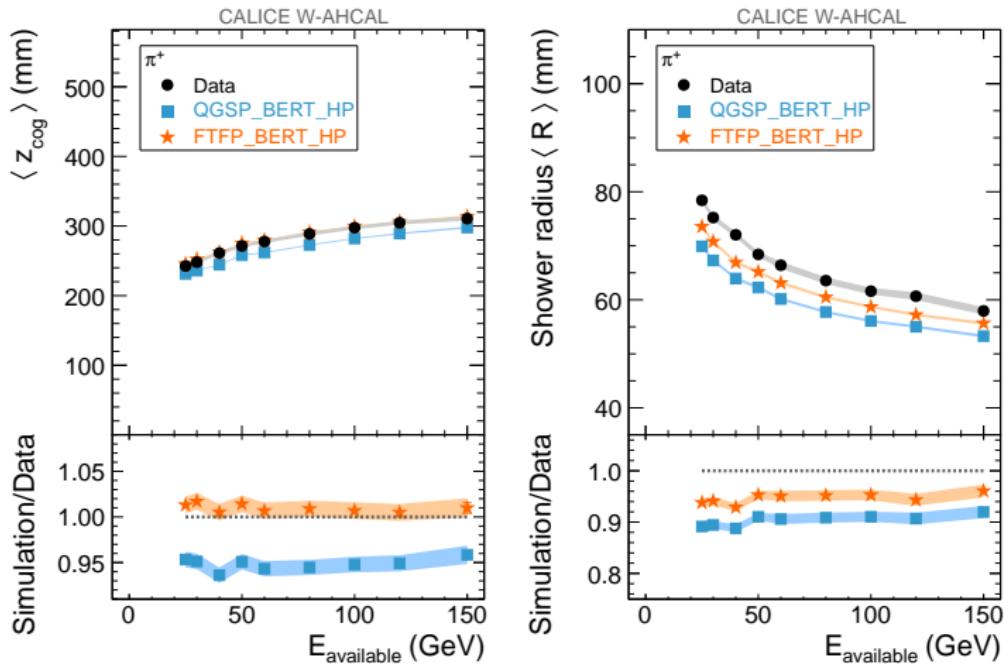
- Hadron  $E_{\text{sum}}$  distributions at high  $p_{\text{beam}}$  have low-energy tail due to leakage
- Geant4 list **QGSP\_BERT\_HP** describes mean slightly better than **FTFP\_BERT\_HP**
- HP = High Precision:** Transports neutrons down to thermal energies, needed for realistic simulation of spallation neutrons in high-A absorbers interacting with scintillator

# Pion resolution



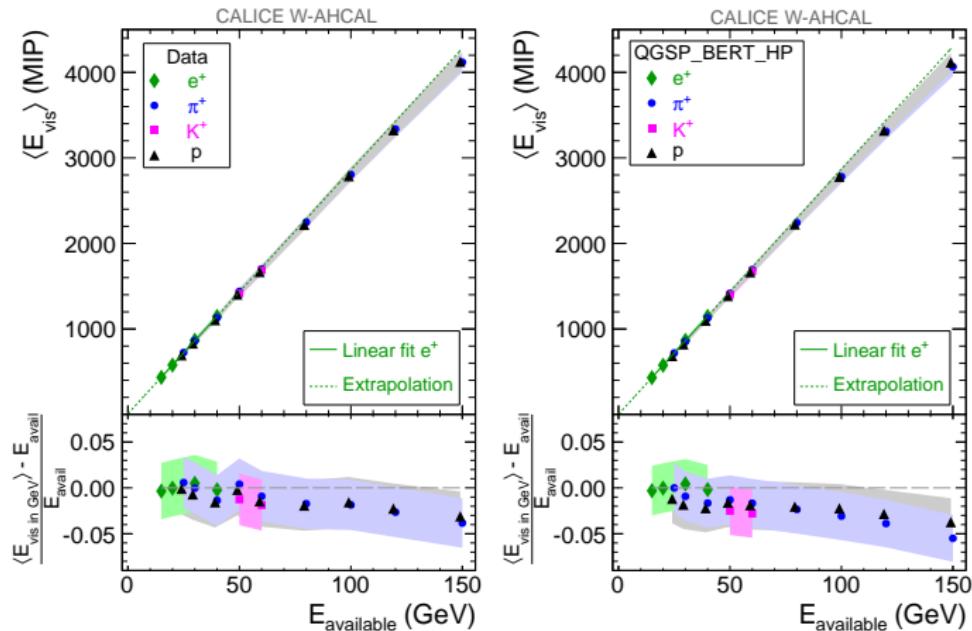
- Energy resolution for  $\pi^+$  follows
$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E[\text{GeV}]}} \oplus b \oplus \frac{c}{E[\text{GeV}]}$$
- Stochastic term:
  - $a = (57.9 \pm 1.1) \% \sqrt{\text{GeV}}$
  - $a = (51.1 \pm 2.8) \% \sqrt{\text{GeV}}$
  - $a = (54.6 \pm 2.0) \% \sqrt{\text{GeV}}$
- $\sigma_E/\langle E \rangle$  lower in MC,
  - by 3–12% for FTFP\_BERT\_HP,
  - by 10–15% for QGSP\_BERT\_HP
- Reminder: For Particle Flow the granularity matters, not the energy resolution

# Pion shower shapes



- $z_{\text{cog}}$ : energy weighted centre of gravity in  $z$ -direction  
 $\langle z_{\text{cog}} \rangle$  well described by **FTFP\_BERT\_HP**, too early showers in **QGSP\_BERT\_HP**
- $R$ : energy weighted shower radius:  
both models underestimate  $\langle R \rangle$ , **FTFP\_BERT\_HP** better

# Comparison of response for different particle types



- Quantify compensation level
- Hadron and positron response agree up to approximately 60 GeV  
→ Onset of leakage in hadron shower
- Behaviour reproduced by MC

# Summary

- Analysis of test beam data of **Si-W-ECAL**

- $\pi^-$  at  $p_{\text{beam}} = 2 \text{ GeV} - 10 \text{ GeV}$
- Study of **hadron shower substructure**
- Comparison to Geant4
  - Energy fraction in interaction region underestimated by 15%
  - Number of secondary tracks well described
- CALICE Analysis Note available at [▶ CALICE Analysis Note 055](#)

- Analysis of test beam data of **W-AHCAL**

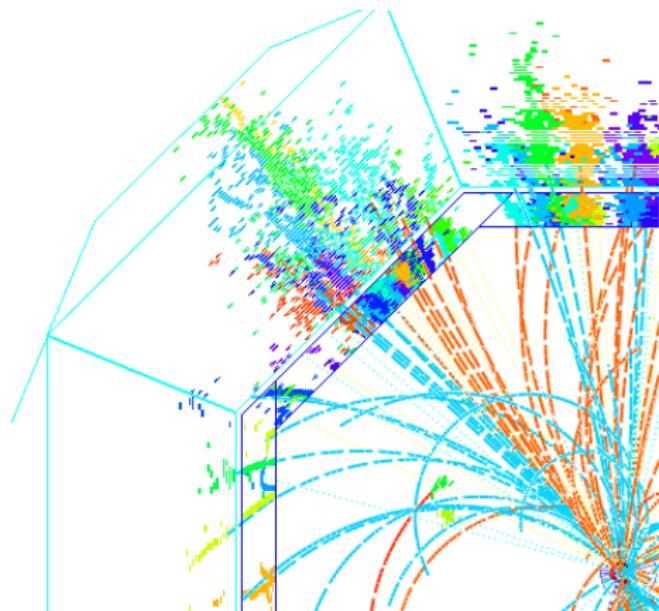
- $e^+$ ,  $\pi^+$ ,  $K^+$ , and  $p$  at  $p_{\text{beam}} = 15 \text{ GeV} - 150 \text{ GeV}$
- Explored SiPM technology and modeling
- Study of **response, energy resolution, and shower shapes**
- Comparison to Geant4
  - High Precision (HP) neutron tracking needed for tungsten simulation
  - Agreement between data and Geant4 lists on few-percent level for average shower properties, within 15% or better for spatial shower profiles
- Publication available at [▶ 2015 JINST 10 P12006](#)

# Backup



# Particle flow calorimetry

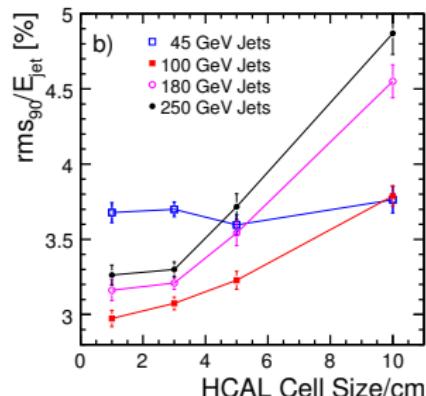
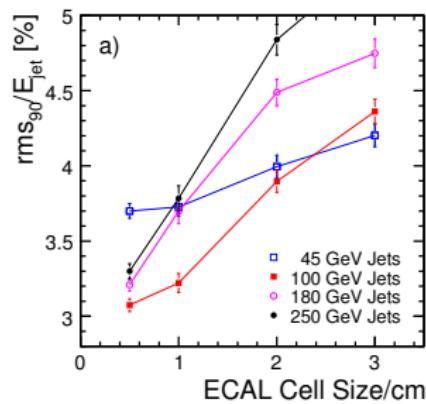
- Jet energy resolution goal
  - 4-3% at ILC
  - 5-3.5 % for 50 GeV-1 TeV jets at CLIC
- Possible solution:  
Fine-grained calorimetry +  
Particle Flow Analysis (PFA)
- What is PFA?
- Typical jet composition:
  - 60% charged particles
  - 30% photons
  - 10% neutral hadrons
- Always use the best information
  - 60% → tracker 😊
  - 30% → ECAL 😊
  - 10% → HCAL 😐



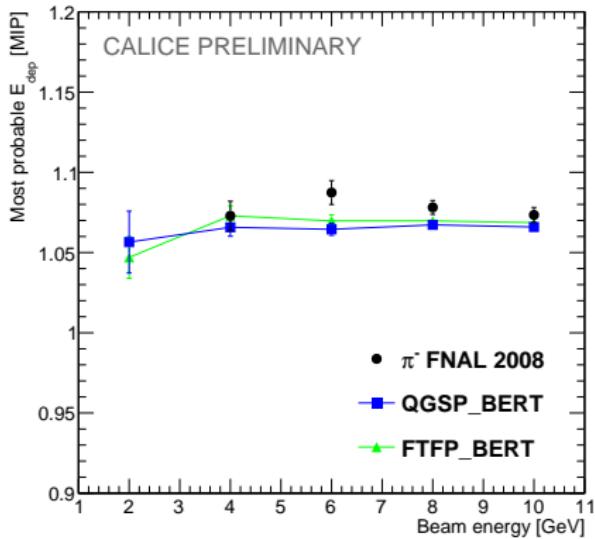
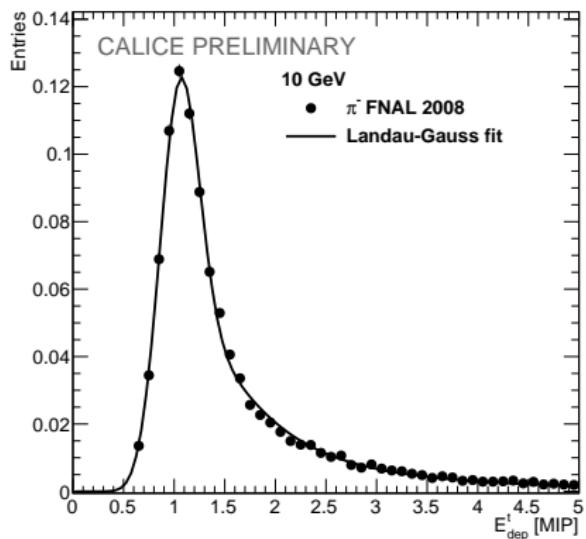
# High granularity calorimeters

NIM A611 2009 25

- PF calorimeters with high granularity allow for an improved jet energy resolution
- High granularity reduces confusion between energy deposits from different primary particles
- ECAL cell size:  $\sim 1 \times 1 \text{ cm}^2$
- HCAL cell size:  $\sim 3 \times 3 \text{ cm}^2$



# Energy depositions by secondary tracks in Si-W-ECAL



- Distribution peaks at 1 MIP as expected for MIPs
- Results are stable over the tested energy range

# Interaction selection criteria in Si-W-ECAL

- Identification of inelastic hadronic interaction in layer =  $i$

- **Absolute energy increase**

- $E_i > E_{\text{cut}}$  &&  
 $E_{i+1} > E_{\text{cut}}$  &&  
 $E_{i+2} > E_{\text{cut}}$

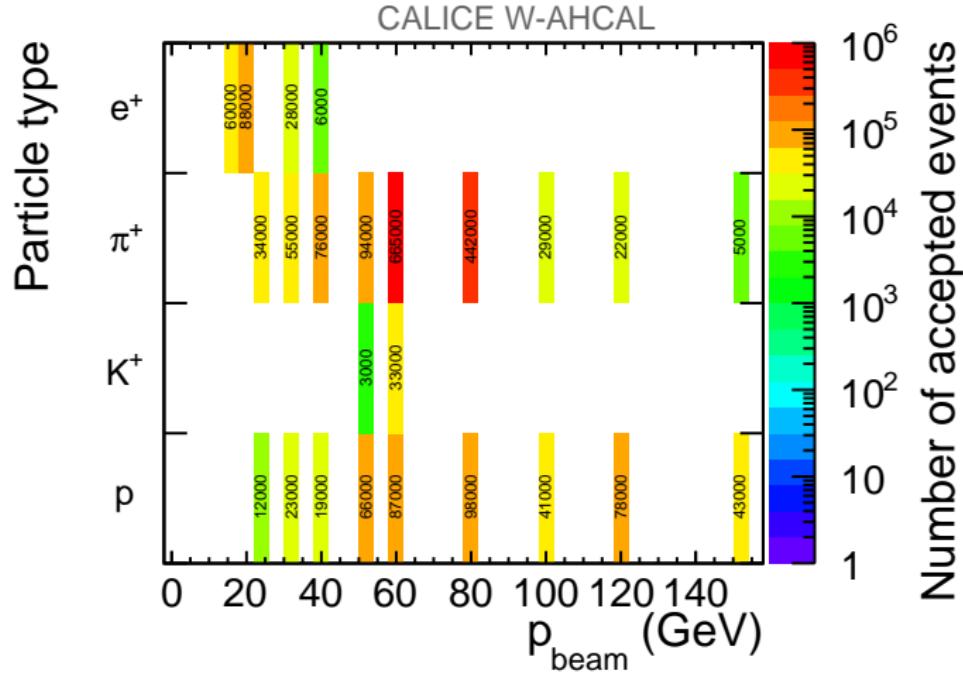
- **Relative energy increase**

- $\frac{E_i + E_{i+1}}{E_{i-1} + E_{i-2}} > F_{\text{cut}}$  &&  
 $\frac{E_{i+1} + E_{i+2}}{E_{i-1} + E_{i-2}} > F_{\text{cut}}$

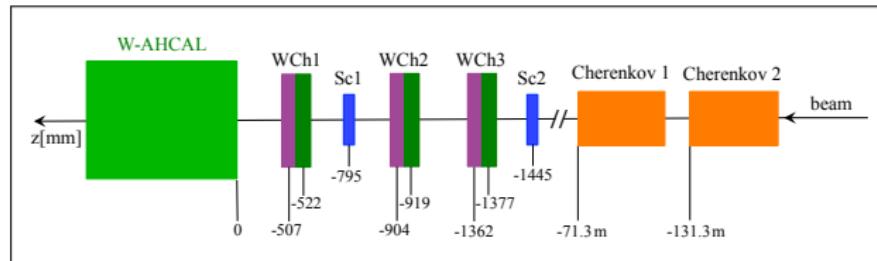
- Empirical values:  $E_{\text{cut}} = 8 \text{ MIP}$ ,  $F_{\text{cut}} = 6 \text{ MIP}$   
 $\rightarrow$  Detection efficiency 60%–93% at 2 GeV–10 GeV
- Detection not trivial at small energies



# Number of W-AHCAL events after selection



# W-AHCAL detector simulation implementation



AHCAL layer as  
implemented in Mokka

- Geant4 detector simulation

- Full setup including beam instrumentation
- Particle generation using gun simulation
- Beam position, direction and spread corresponding to data runs

- Digitisation

- Realistic detector granularity
- Optical cross talk between scintillator tiles
- Birks' law
- Readout electronics: signal shaping time, noise
- Saturation effects



# Scintillator and SiPM Characterisation

- Improve understanding of scintillators and SiPMs
- Dedicated lab for scintillator and SiPM testing
- Test bench: electron gun, DUT on movable table, trigger scintillators, read-out electronics
- Study uniformity of response, cross-talk, ...

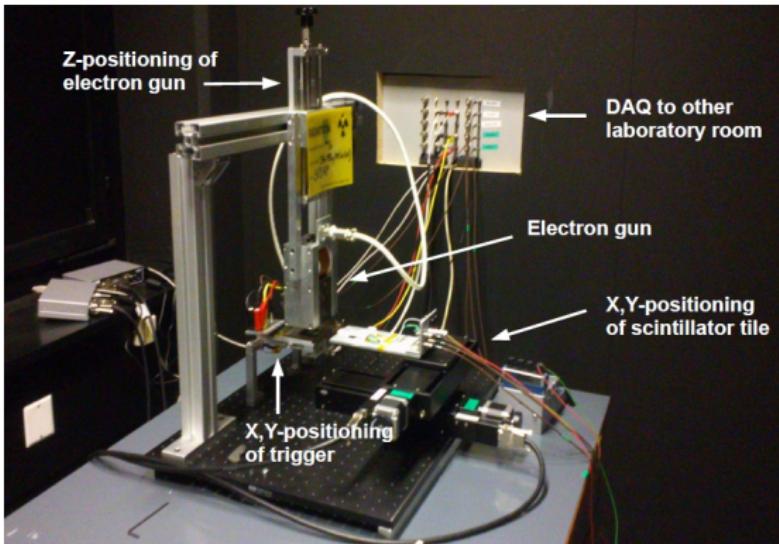
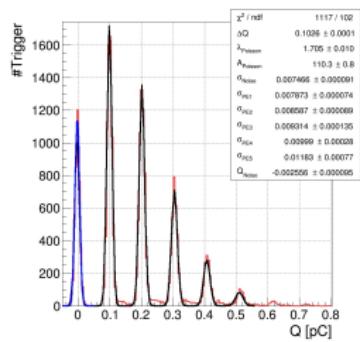


Photo-electron spectrum of SiPM



Calibrated Scint+SiPM response

