Comparison of test beam data from imaging calorimeters with GEANT4 simulations

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on behalf of the CALICE collaboration

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Prototypes for highly granular calorimeters

- **Tracker**: Silicon ECAL
- **ECAL**: Scintillator ECAL
- **HCAL**: Analog HCAL, Semi-Digital HCAL, Digital HCAL
- **Muon system**: RPCs

**Readout**
- Silicon PIN diodes
- Scint. strips + Silicon Photo Multipliers
- RPCs (µMegas)
- RPCs (GEMs)

**Granularity (mm³)**
- 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
CALICE test beam experiments

- Test beam experiments in 2006-2012 at DESY, CERN, FNAL
- Prototypes of up to $\sim 1\,\text{m}^3$, $\sim 2\,\text{m}^3$ including Tail Catcher
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
Validation of Detector Simulation using Electron Data
Si-W-ECAL: Electron linearity and resolution

- Electromagnetic processes well understood
- Cross check detector calibration
- Understand requirements for details needed in simulation

Electrons at 6-45 GeV
Reconstructed energy of data and simulation agree within 1 %

Linearity: \( E_{\text{rec}} \) versus \( E_{\text{beam}} \), agreement with linear dependence within 1 %

Energy resolution: \( \sigma_E \approx a \sqrt{E} \oplus b \rightarrow 16.6\% \sqrt{E} \oplus 1.1\% \), 17.0\%

\[ \sqrt{E} \oplus 0.8\% \]

30 GeV e−
Linearity Energy resolution

Geant4 version 9.3

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Geant4 Comparison to CALICE Data
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Electrons at 6-45 GeV

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Energy resolution: \( \frac{\sigma_E}{E} \approx \frac{a}{\sqrt{E}} + b \rightarrow \frac{16.6\%}{\sqrt{E}} \oplus 1.1\%, \frac{17.0\%}{\sqrt{E}} \oplus 0.8\% \)
Sc-Fe-AHCAL: Positron linearity and resolution

- Positrons at 10-50 GeV
- Reconstructed energy of data and simulation agree within 3%  
- Agreement with linearity within 3% (1% up to 30 GeV)  
- Energy resolution $\frac{21.9\%}{\sqrt{E}} \oplus 1.0\%$, $\frac{21.5\%}{\sqrt{E}} \oplus 0.7\%$  
- Corrections are under control, e.g. saturation  

2011 JINST 6 P04003  
Geant4 Comparison to CALICE Data  
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Sc-W-AHCAL: Positron linearity and resolution 1-6 GeV

- Positrons at 1-6 GeV
- Reconstructed energy in data and simulation agree within 2%, resolution within 5%
- Stochastic term of energy resolution $a = 29.6\%$, $a = 29.2\%$
  → Coarser sampling in W than in Fe
Geant4 Comparison to Hadron Data
Si-W-ECAL: Fraction of interacting pions

- Pions at 2-10 GeV and 8-80 GeV in Si-W-ECAL
- Highly granular calorimeter allows to study shower shape and substructure

Study fraction of interacting pions in Si-W-ECAL of $\sim 1\lambda_l$ ($24X_0$)
- Models agree with data at $\leq 4$ GeV
- At 6-10 GeV, the models overestimate the interacting fraction by 4%

Energy deposition (a.u.)

x direction (pad number)

z direction (layer number)

Incoming pion energy [GeV]

Interaction fraction

Models agree with data at $\leq 4$ GeV
At 6-10 GeV, the models overestimate the interacting fraction by 4%
Si-W-ECAL: Longitudinal and radial energy profile

- Models deposit too much energy near the interaction layer
- Effect increasing with beam momentum
- Radial energy profiles best described by QBBC
- FTFP models deposit energy too close to shower axis, QGSP_BERT shows opposite effect
- Hit distributions (longitudinal and radial) are well reproduced by MC
Sc-Fe-AHCAL: Pion linearity

- Pions at 8-100 GeV

**FTFP_BERT** performance varies with Geant4 version

- Lists including BERT-model agree within 4% at low energies, within 10% at high energies
Sc-Fe-AHCAL: Analogue vs (semi-)digital readout

- Comparison of 3 readout options using same prototype and dataset of pions at 10-80 GeV
  - Analogue: Measure energy deposition
  - Digital: Count number of hits above threshold $N_{\text{hits}}$
  - Semi-digital: Count number of hits above thresholds $N_1$, $N_2$, and $N_3$

**Geant4 version 9.6.p01**

- Agreement between data and FTFP_BERT in digital and semi-digital read-out within ±10%
- Digital MC resolution shifted to lower energies

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Geant4 version 9.6.p01

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- Digital MC resolution shifted to lower energies
Sc-Fe-AHCAL: Parametrisation of hadron shower profiles

- Logitudinal and radial shower shape for pions and protons at 10-80 GeV
- Fit of longitudinal shower shape using

$$\Delta E = A \cdot \left\{ \frac{f \cdot \exp(-\frac{z}{\beta_{\text{short}}})}{\beta_{\text{short}} \cdot \Gamma(\alpha_{\text{short}})} \cdot \left( \frac{z}{\beta_{\text{short}}} \right)^{\alpha_{\text{short}}-1} + \frac{(1-f) \cdot \exp(-\frac{z}{\beta_{\text{long}}})}{\beta_{\text{long}} \cdot \Gamma(\alpha_{\text{long}})} \cdot \left( \frac{z}{\beta_{\text{long}}} \right)^{\alpha_{\text{long}}-1} \right\}$$
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\[
\Delta E = A \cdot \left\{ f \cdot \frac{\exp\left(-\frac{z}{\beta_{short}}\right)}{\Gamma(\alpha_{short})} \cdot \left(\frac{z}{\beta_{short}}\right)^{\alpha_{short}-1} + \frac{(1-f) \cdot \exp\left(-\frac{z}{\beta_{long}}\right)}{\Gamma(\alpha_{long})} \cdot \left(\frac{z}{\beta_{long}}\right)^{\alpha_{long}-1} \right\}
\]

- MC overestimates fraction of short component except FTFP_BERT for protons

- Tail parameters well described by MC
Sc-W-AHCAL: Pion, proton and kaon response

- Pion, protons and kaons at 3-10 GeV
- Good agreement between data and QGSP\_BERT\_HP and FTFP\_BERT\_HP
- QGSP\_BIC\_HP underestimates data slightly (within uncertainties)
Sc-W-AHCAL: Proton shower shapes

- **QGSP_BERT_HP** and **QGSP_BIC_HP** overestimate energy deposition in first part of shower
- Radial profile: Models overestimate energy density in shower core

**Geant4** version 9.5.p01

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Sc-Fe-AHCAL: Substructure of hadronic shower

- Pions at 10-80 GeV in AHCAL
- Identify track segments of minimum-ionising particles within hadron showers
- Best agreement between data and QGSP_BERT and FTFP_BERT
- Agreement crucial for simulation studies of Particle Flow Analysis
Fe-SDHCAL: Substructure of hadronic shower

- Pions at 10-80 GeV in SDHCAL
- Identify track segments of minimum-ionising particles within showers
- Best agreement between data and QGSP_BERT and FTFP_BERT
- Agreement crucial for simulation studies of Particle Flow Analysis
T3B: Time structure of hadronic showers

- Time structure of hadronic showers
  - Delayed component due to nuclear deexcitation, neutron propagation etc.

- Pions in **tungsten** show more late hit time entries than **steel**

- Reference measurement of **muons**

**T3B**: Tungsten Timing Test Beam
- Scintillator cells placed behind HCAL
- Read out $3000 \times 800 \text{ ps} \approx 2 \mu \text{s}$ to sample the full shower development

CAN-038  arXiv:1404.6454
T3B: Time distribution

- High precision (HP) neutron tracking improves agreement for tungsten
- Late energy deposits are more important in the outer regions of a shower
Summary

- Test beam experiments with ECAL and HCAL prototypes
  - Test of novel technologies in large-scale calorimeters
  - Demonstration of detector calibration capabilities
  - Characterisation of prototypes: linearity, resolution
  - Measurement of particle shower evolution

- Validate detector simulations using electromagnetic processes
  - Overall good agreement between data and detector simulation

- Test models of hadronic nuclear interactions
  - Geant4 models reproduce hadronic data within few percent
  - High precision (HP) neutron tracking improves tungsten HCAL simulation
  - Novel test of shower substructure and time structure

- Stay tuned for more CALICE results, e.g. HCALs with gaseous readout
Backup
CALICE

- CAlorimetry for LInear Collider Experiments
- International R&D collaboration, ~330 members
- Development of imaging calorimeters for experiments at high-energy $e^+e^-$ colliders

- Build and test calorimeter prototypes
- Demonstrate that the required performance of the calorimeter system can be achieved
- Compare results to MC predictions
Calorimeters for future lepton colliders

- **Jet energy resolution goal**
  - 5-3.5% for 50 GeV to 1 TeV jets

- **Possible solution**
  - Particle Flow Analysis
    - Low mass tracker for charged particles
    - High granularity ECAL for photons
    - High granularity HCAL for neutral hadrons

- CALICE builds and tests prototypes of highly granular calorimeters
- Demonstration that the required performance of the calorimeter system can be achieved
- Comparison of results to MC predictions
International Linear Collider (ILC)

- Superconducting RF cavities
- Gradient: 32 MV/m
- Energy: $\sim 500$ GeV (upgradable to 1 TeV)
- Luminosity: few $10^{34}$ cm$^{-2}$s$^{-1}$
Compact Linear Collider (CLIC)

- 2-beam acceleration scheme
- Operated at room temperature
- Gradient: 100 MV/m
- Energy: \( \sim 375 \text{ GeV} \) to 3 TeV
- Luminosity: few \( 10^{34} \text{ cm}^{-2} \text{s}^{-1} \)
Detector simulations: Example Sc-W-AHCAL

- **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 neighbouring scintillator tiles
  - Birk’s law
  - Simulated readout electronics: signal shaping time, noise
  - Saturation effects