CALICE AHCAL simulations

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Outline

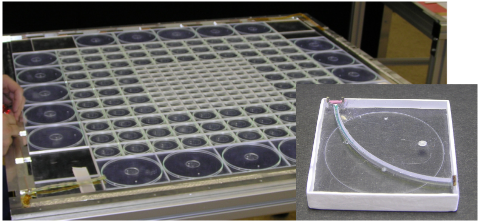
1. The highly granular CALICE AHCAL
2. Digitisation of AHCAL simulations
3. Calorimetric observables for hadronic shower studies: standard and unique
4. Secondaries in hadronic showers from MC-truth

Real detector layout and composition

CALICE AHCAL: scintillator-SiPM analog hadron calorimeter – baseline option for ILD HCAL

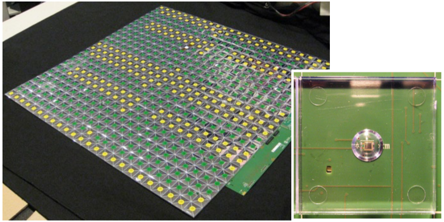
Physics AHCAL prototype

- sensor: **scintillator + WLS fiber + SiPM**
- rad: tiles 3×3, 6×6, 12×12 cm^2, ~90×90 cm^2
- lng: steel (2 cm) or W(1 cm), scint. 5 mm
- 38 layers, $\sim 5.3\lambda_I$, 7608 tiles in total
- tile side coating, external electronic boards
- **Overview of data-MC comparisons for physics prototype (Geant4 up to v10.1) and references to publications can be found** here



Technological AHCAL prototype

- sensor: **scintillator+SiPM** (direct readout)
- rad: tiles 3×3 cm^2, ~72×72 cm^2
- lng: steel (2 cm), scint. 3 mm
- 38 layers, $\sim 4.5\lambda_I$, 21888 tiles in total
- tiles indiv. wrapped in foil, embedded electr.
- **In this talk, focus is on simulations of technological prototype and hadronic models from Geant4 v10.3.**



Detector model and simulation conditions

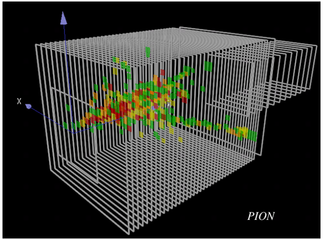
TB data and reconstruction

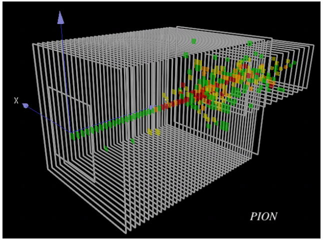
- standalone AHCAL at CERN SPS in 2018 (one of configs with small tail catcher)
- muons, electrons and pions (10–200 GeV)
- mip calibration to equalise cell response (good for 99.9% of channels)
- ILCSoft-based reconstruction software
- dedicated particle ID for test beam data

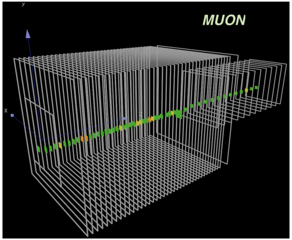
Simulations

- **Geant4 v10.3, FTFP_BERT_HP, QGSP_BERT_HP**
- detailed detector geometry and material composition, perfect alignment
- beam profiles from TB data
- digitisation to account for light collection, photodetection efficiency, SiPM saturation, noise (cell parameters from test beam DB)

Colours on event display correspond to hit amplitudes from low (<3 MIP) to high (>5.5 MIP)







For data and MC: the same reconstruction chain and 0.5-MIP threshold for analysis

Data-driven digitisation chain

Ionis. loss to MIP: $A_{\mathrm{MIP}} = A_{\mathrm{ion}}/C_{\mathrm{MIP}}$, $C_{\mathrm{MIP}} = 481$ keV/MIP for μ in 3 mm scint. ⇒

MIP to Light Yield: $A_{\mathrm{pix}} = A_{\mathrm{MIP}} \cdot C_{\mathrm{LY}}$, $C_{\mathrm{LY}} \approx 14$ pixel/MIP, cell-wise from DB ⇒

SiPM saturation: $A_{\mathrm{sat}} = N_{\mathrm{eff}} \cdot (1 - exp(-A_{\mathrm{pix}}/N_{\mathrm{eff}})$ with linear extrapolation at limit, $N_{\mathrm{eff}} = 2668$, SiPM nominal from DB ⇒

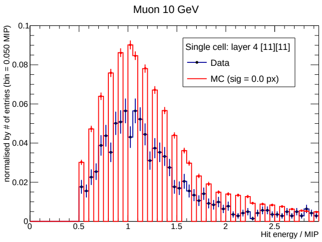
⇒ Binomial smearing ⇒

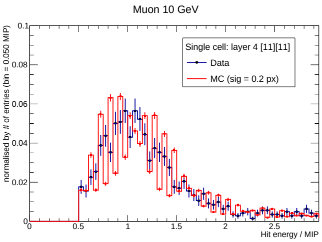
Gaussian smearing with $\sigma_{\mathrm{Gauss}} = 0.3$ pixel from comparison with data ⇒

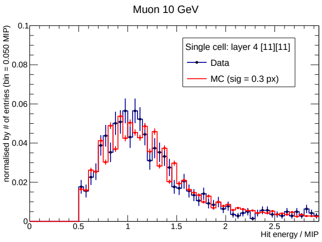
Conversion from pixel to ADC: $A_{\mathrm{ADC}} = A_{\mathrm{sat}} \cdot C_{\mathrm{gain}}$, $C_{\mathrm{gain}} \approx 16$ ADC/pixel, cell-wise from DB ⇒

Time smearing (Gauss, 1ns)

Muon track hits in a single cell with different Gaussian smearing of MC





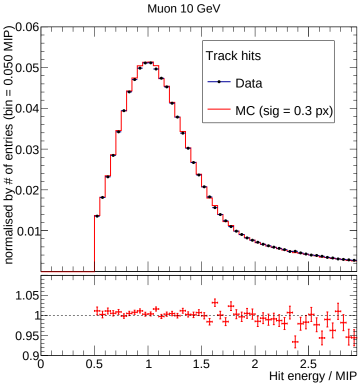


Data: ~1500 entries / hist; MC: >10000 entries / hist

Digitisation results: muon track hit energy spectra

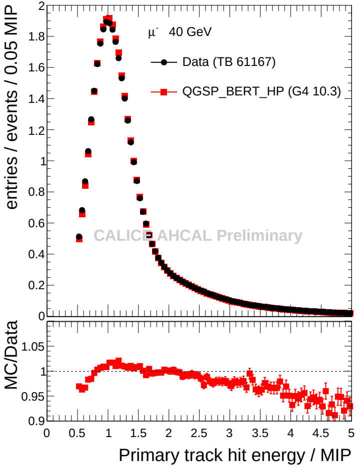
Track hits of 10 GeV muons

- used for digitisation tuning at single cell level
- huge statistics: >1 mln. entries / hist in data and >2 mln. entries / hist in MC
- very good data-MC agreement



Crosscheck on 40 GeV muons

- same digitisation conditions as for 10 GeV
- agreement within 2% around 1 MIP



Digitisation: from CALICE AHCAL to ILD HCAL

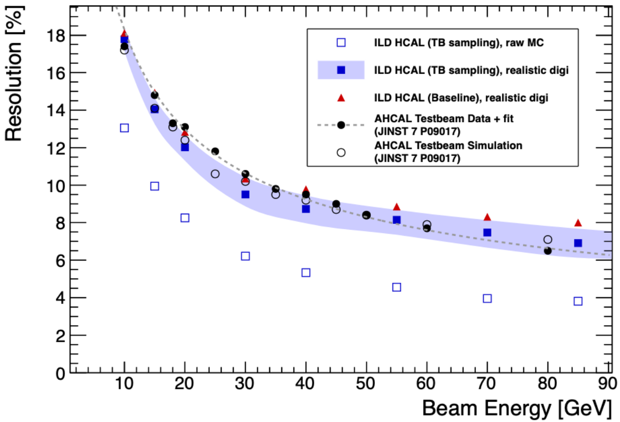
Digitisation in ILD simulations

- full ILD simulation using QGSP_BERT_HP physics list from Geant4 version 9.5p2
- comparison with the results from the AHCAL physics prototype
- details in the **thesis of Oskar Hartbrich** (2016, Chapter 5)
  ▸ link to full text

Digitisation effect

- Implementation of digitisation results in agreement of ILD simulations with AHCAL simulations and TB results
- Realistic digitisation worsens resolution by ∼4–5%

Relative resolution for hadrons



Plot from the ▸ thesis *of Oskar Hartbrich*

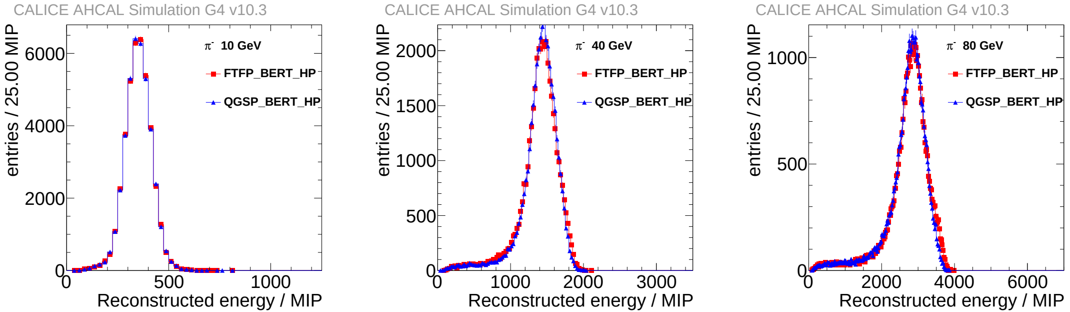
Main calorimetric observable: reconstructed energy

Simulated single π^- in the CALICE AHCAL

Event selection: the identified shower start at 3-6 layers of the AHCAL for shower containment

- algorithm to find the position of first inelastic interaction (shower start) is implemented in caliceSoft
- no specific clustering, all hits beyond the found shower start are considered to belong to the shower

Reconstructed energy is the sum of hit energies



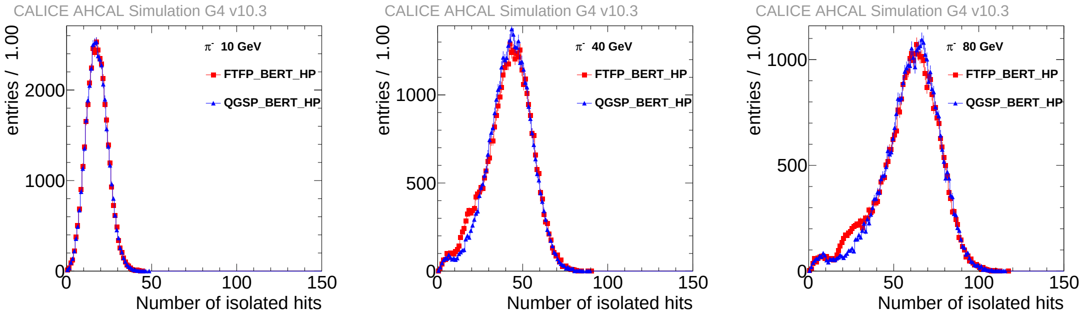
- leakage minimised due to event selection, no noticeable differences between models
- **New calorimetric observables can be introduced to reveal differences between models.**

Calorimetric observable: number of isolated hits

New calorimetric observables help to reveal differences between models.

Number of isolated hits within a hadronic shower (beyond the found shower start layer)

isolation: 0 neighbours in a cube of 3×3×3 cells around the hit

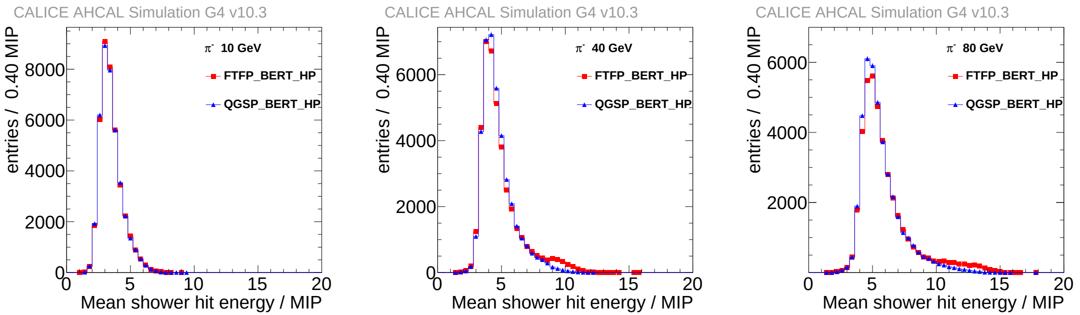


- Bertini cascade at 10 GeV invoked for both models - similar distributions
- non-smooth behaviour of FTFP_BERT_HP above 10 GeV

Calorimetric observable: mean shower hit energy

Mean energy of hits within a hadronic shower

average over all shower hits beyond the found shower start layer

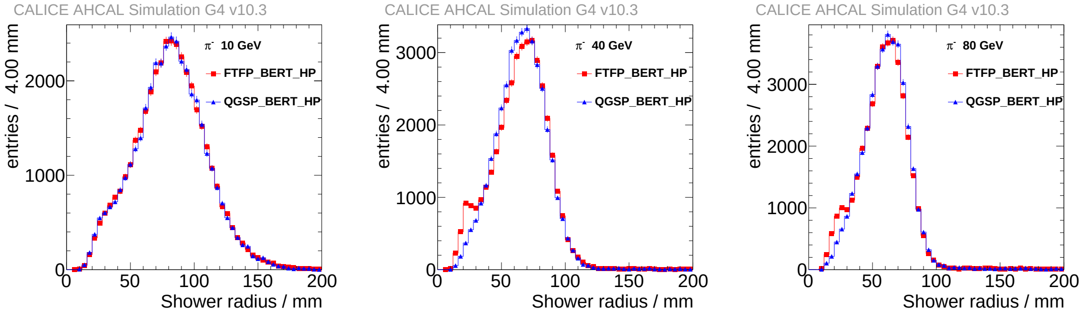


- Bertini cascade at 10 GeV invoked for both models - similar distributions
- **more events with very high mean hit energy is predicted by FTFP_BERT_HP above 10 GeV**
- **more smooth distributions predicted by QGSP_BERT_HP**

Calorimetric observable: shower radius

Mean energy weighted hit distance from shower axis

$R_{\rm sh} = \frac{\sum_{i=1}^{N_{\rm sh}} e_i \cdot r_i}{\sum_{i=1}^{N_{\rm sh}} e_i}$, $r_i = \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2}$ - hit radial distance from shower axis (x_0, y_0),
shower axis is taken from primary track or radial centre of gravity

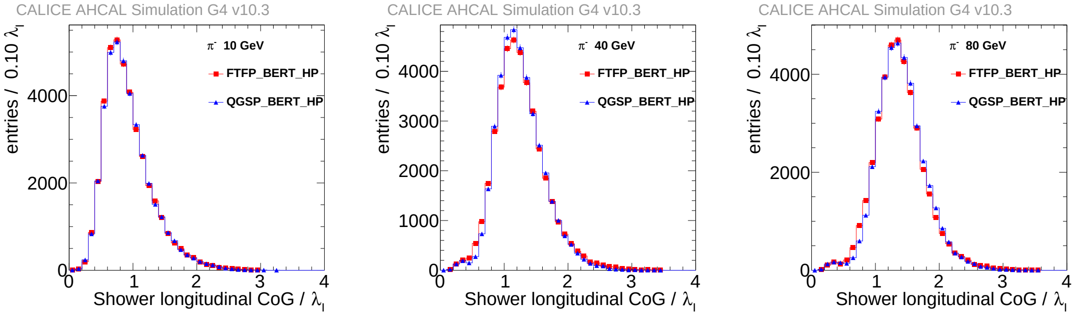


- Bertini cascade at 10 GeV invoked for both models - similar distributions
- **more events with small shower radius is predicted by FTFP_BERT_HP above 10 GeV**
- **more smooth distributions predicted by QGSP_BERT_HP**

Calorimetric observable: longitudinal centre of gravity

Mean energy weighted hit distance from shower start

$$Z_{\mathrm{CoG}} = \frac{\sum_{i=1}^{N_{\mathrm{sh}}} e_i \cdot (z_i - z_{\mathrm{start}})}{\sum_{i=1}^{N_{\mathrm{sh}}} e_i}$$, z_{start} - long. coord. of shower start



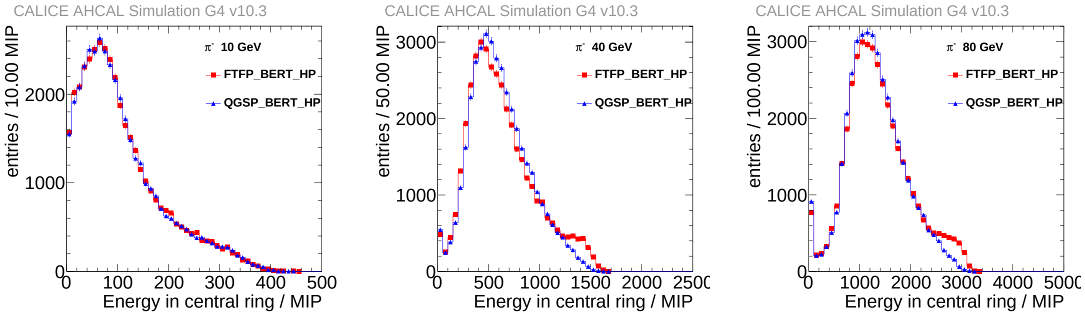
- consistent predictions from both models
- maximum is around 1 nuclear interaction length and increases with energy as expected

Calorimetric observable: energy in central ring

Additional "ring" observables (integrated over longitudinal depth)

- 3-cm wide rings around shower axis, 12 rings in total
- number of isolated hits energy sum in a cylinder, E_i^{ring}

Example: energy in the innermost cylinder around shower axis

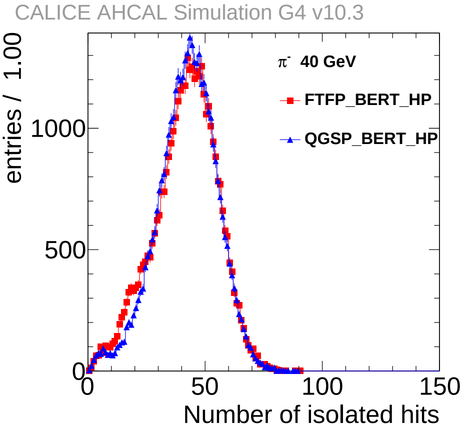


- Bertini cascade at 10 GeV invoked for both models - similar distributions
- more events with high energy density in the centre predicted by FTFP_BERT_HP above 10 GeV
- more smooth distributions predicted by QGSP_BERT_HP

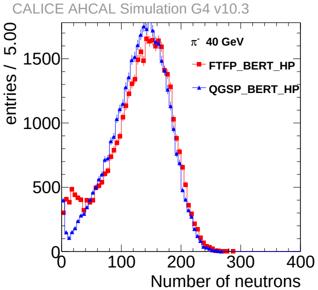
Number of isolated hits vs. number of neutrons in a shower at 40 GeV

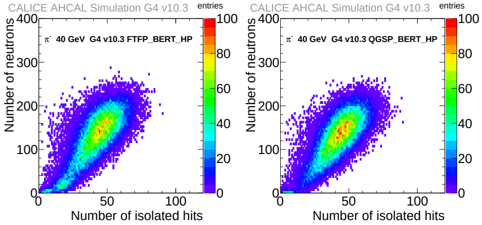
N.B.: neutrons, which have one parent only that is also neutron, are not counted to avoid double counting

Calorimetric observable: number of isolated hits



MC truth: number of neutrons



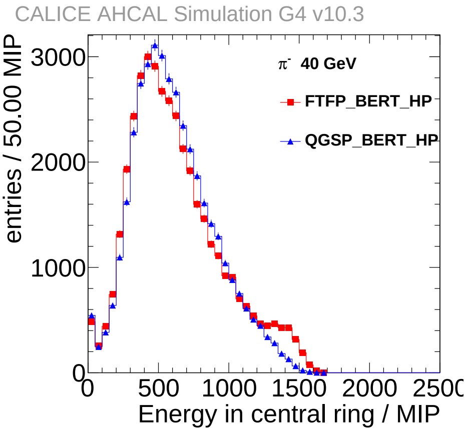


Different behaviour for both calorimetric and MC-truth

Visible correlation between N_{iso} and N_{neutron}

Energy in central ring vs. energy of π^0s in a shower at 40 GeV

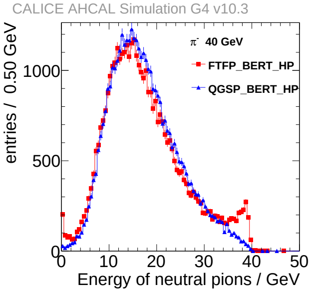
Calorimetric observable: energy in innermost ring

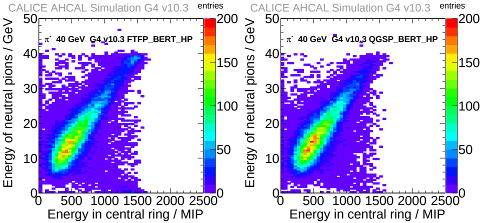


Different behaviour of physics lists at limit

Visible correlation between $E^{\mathrm{ring}}_{\mathrm{central}}$ and E_{π^0}

MC truth: energy of π^0s





Summary

Simulation of the AHCAL

- **Geant4 version 10.3, FTFP_BERT_HP and QGSP_BERT_HP physics lists**
- digitisation sequence accounts for nonsimulated detector effects:
  scintillation light collection, photodetection efficiency, SiPM saturation, electronic noise
- digitisation is tuned by comparison of response to muons in data and simulations
- **good agreement between data and simulations at MIP level**

Comparison of Geant4 hadronic models

- For standard observable, **good agreement** between models is observed in prediction of **reconstructed energy** in the range 10-80 GeV.
- **New "high-granular" observables** have been introduced (number of isolated hits, mean hit energy, shower radius and longitudinal centre of gravity), which help to **reveal differences between models**:
  - more smooth behaviour of QGSP_BERT_HP
  - peculiarities of FTFP_BERT_HP observed at the edges of kinematic region
- Correlation of calorimetric observables with MC truth can help to predict parameters of secondaries within a hadronic shower (some preliminary results can be found here).

Comparisons with data in progress and coming soon!

Backup slides

Single negative pions in the CALICE AHCAL

Event selection: the identified shower start at 3-6 layers of the AHCAL

- algorithm to find the position of first inelastic interaction (shower start) is implemented in caliceSoft
- no specific clustering, all hits beyond shower start are considered to belong to the shower

Counting and amplitude observables

- **Number of isolated hits**, $N_{\rm iso}$ [isolation – 0 neighbours in a cube of 3×3×3 cells around the hit]
- **Number of track hits**, $N_{\rm trk}$ [defined as having 2 in-line neighbours and MIP-like deposition]
- **Mean shower hit energy**, $\langle e_{\rm hit} \rangle$
- **Shower radius** $R_{\rm sh} = \frac{\sum_{i=1}^{N_{\rm sh}} e_i \cdot r_i}{\sum_{i=1}^{N_{\rm sh}} e_i}$, $r_i = \sqrt{(x_i - x_0)^2 + (y_i - y_0)^2}$ - hit radial distance from shower axis (x_0, y_0)
- **Longitudinal shower centre of gravity** $Z_{\rm CoG} = \frac{\sum_{i=1}^{N_{\rm sh}} e_i \cdot (z_i - z_{\rm start})}{\sum_{i=1}^{N_{\rm sh}} e_i}$, $z_{\rm start}$ - long. coord. of shower start

  e_i - energy of hit with coordinates x_i, y_i, z_i; $N_{\rm sh}$ - number of shower hits

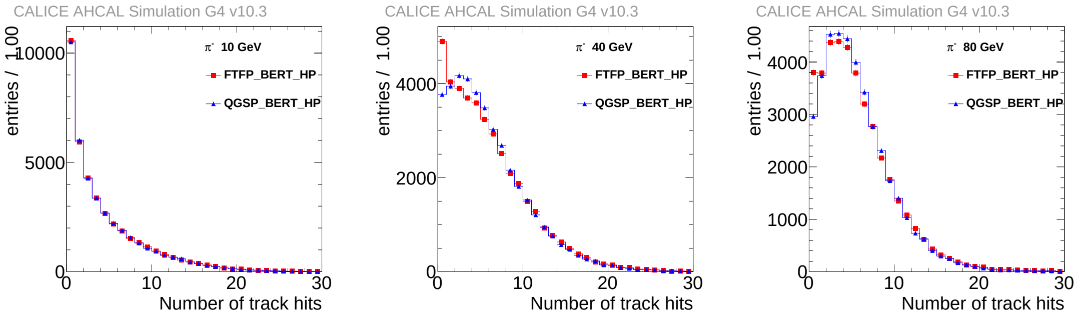
Additional "ring" observables (integrated over longitudinal depth)

- 3-cm wide rings around shower axis, 12 rings in total
- number of isolated hits in a ring and energy sum in a ring, $E_{\rm i}^{\rm ring}$

Calorimetric observable: number of track hits

Number of track hits within a hadronic shower

track hit has only 2 neighbours arranged in line and MIP-like deposition (<5 MIP)



- Bertini cascade at 10 GeV invoked for both models - similar distributions
- **smaller number of track hits is predicted by FTFP_BERT_HP above 10 GeV**

Pion-induced showers in the CALICE AHCAL

- **Geant4 v10.3**, physics lists: FTFP_BERT_HP and QGSP_BERT_HP
- negative pions @ 10–80 GeV, about 500 kevt / sample (centrally produced by CALICE DESY group)
- digitisation: GeV-to-MIP conversion based on simulated muons, implementation of detector effects (SiPM pixel statistics and saturation), added noise from data samples

Parameters of secondaries at generator level are extracted from MCParticle collection

Neutral pions

are counted independently of their parents (some of them might be from η mesons)

- **Number of neutral pions in an event, N_{π^0}**
- **Sum of the energies of neutral pions, E_{π^0}**

Neutrons

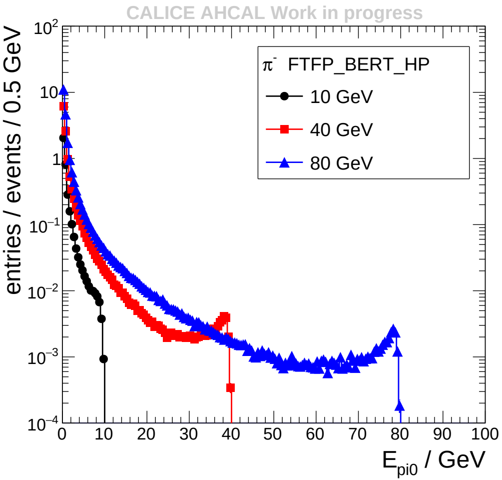
are counted except for those that have one parent only that is also neutron (to avoid double counting)

- **Number of neutrons from interactions, $N_{neutron}$**
- **Sum of kinetic energies of neutrons from interactions, $T_{neutron}$**

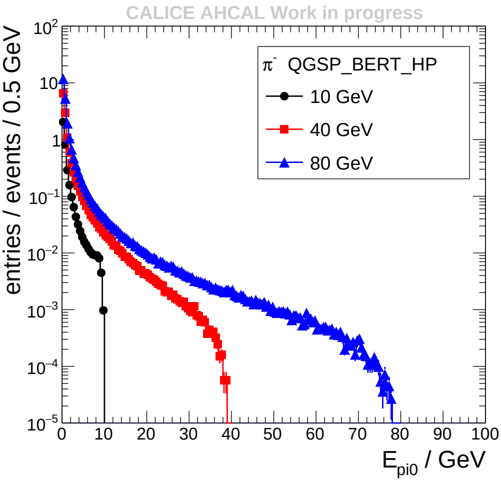
MC-truth: energy spectra of neutral pions in hadronic shower

Legend: **10 GeV**, **40 GeV**, **80 GeV** (∼100 kevt / sample after selections)

FTFP_BERT_HP



QGSP_BERT_HP

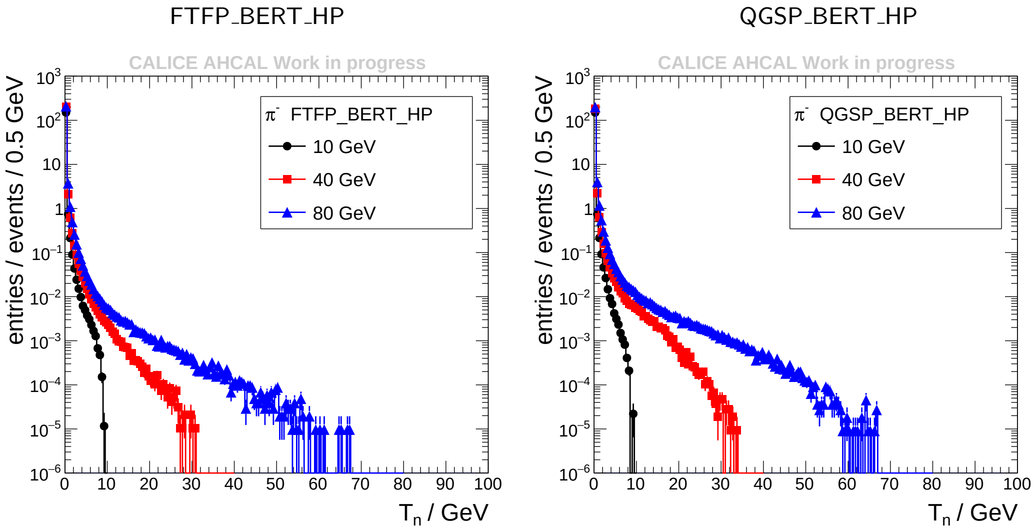


Very different spectra from FTFP and QGSP models above 10 GeV.

Similar behaviour at 10 GeV due to the same Bertini model (BERT) in this energy range.

MC-truth: spectra of neutron kinetic energy in hadronic shower

Legend: **10 GeV**, **40 GeV**, **80 GeV** ($\sim$100 kevt / sample after selections)



Different shape of high energy tails from FTFP and QGSP models. Neutron energy cut is set to 1 MeV.
Similar behaviour at 10 GeV due to the same Bertini model (BERT) in this energy range.