Exploring the structure of hadronic showers and the hadronic energy reconstruction with highly granular calorimeters

Vladimir Bocharnikov (DESY)
on behalf of the CALICE Collaboration

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Highly granular calorimeters

Motivation

Planned experiments at lepton colliders

ILC, CLIC, CEPC, FCCee, … detector concepts: ILD,SiD, …

- **precision frontier**: measurements of Higgs couplings, W, Z and top properties, searches for BSM physics
- model-independent analyses possible
- clean environment

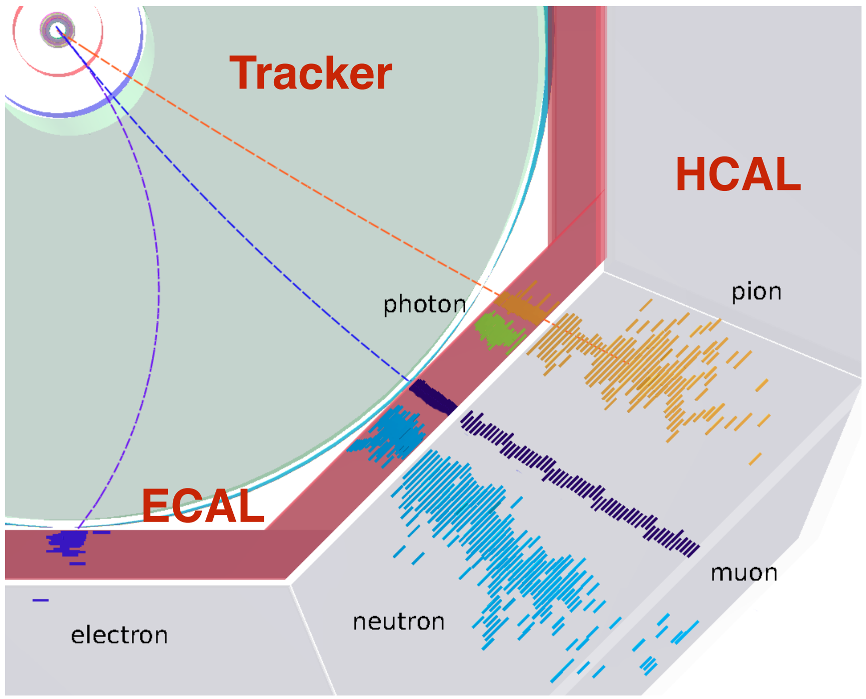
Goal: 3-4% jet energy resolution (~50-250 GeV)

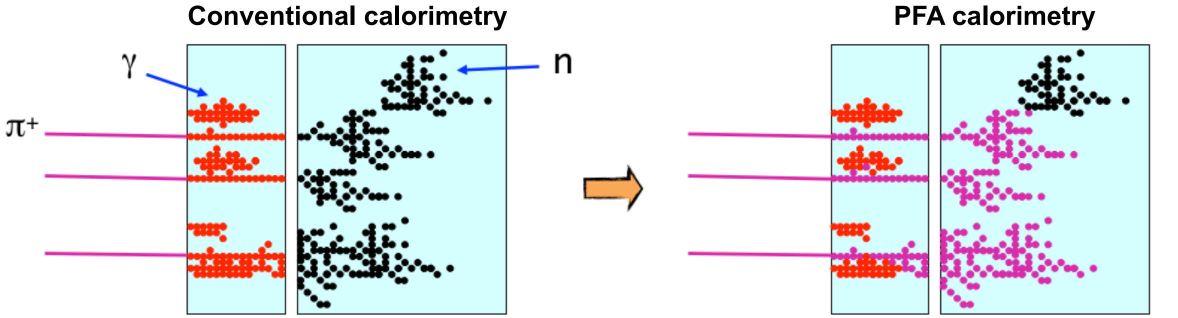
to distinguish di-jets from W and Z hadronic decays

Particle Flow Approach - promising solution for jet energy reconstruction with best suited detectors depending on particle type within a jet

- Used in CMS and ATLAS
- Better performance can be achieved with
  - **High granularity** of calorimeter system

Not only lepton colliders: CMS HGCAL, DUNE ND…



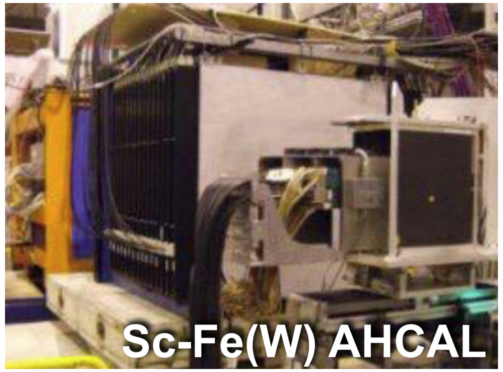


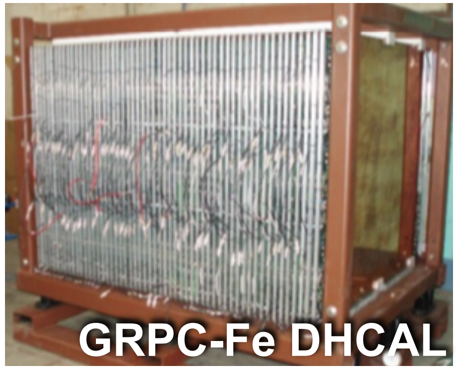
$E_{JET} = E_{ECAL} + E_{HCAL}$ $\quad$ $E_{JET} = E_{TRACK} + E_{\gamma} + E_{n}$

CALICE developments of highly granular calorimeters

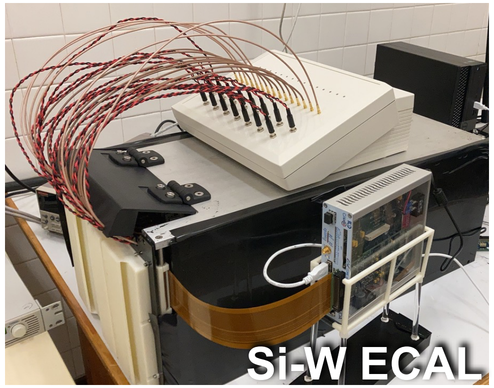
Since 2005. Semi-conductor, scintillator and gaseous read-outs

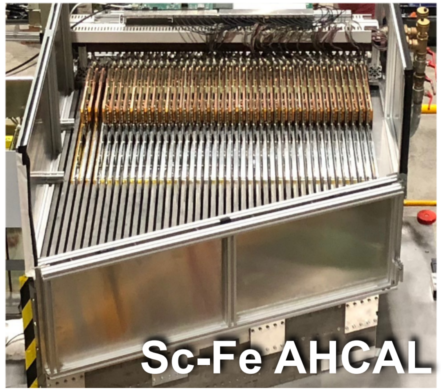
Proof-of-principle physics prototypes





Second generation technological prototypes



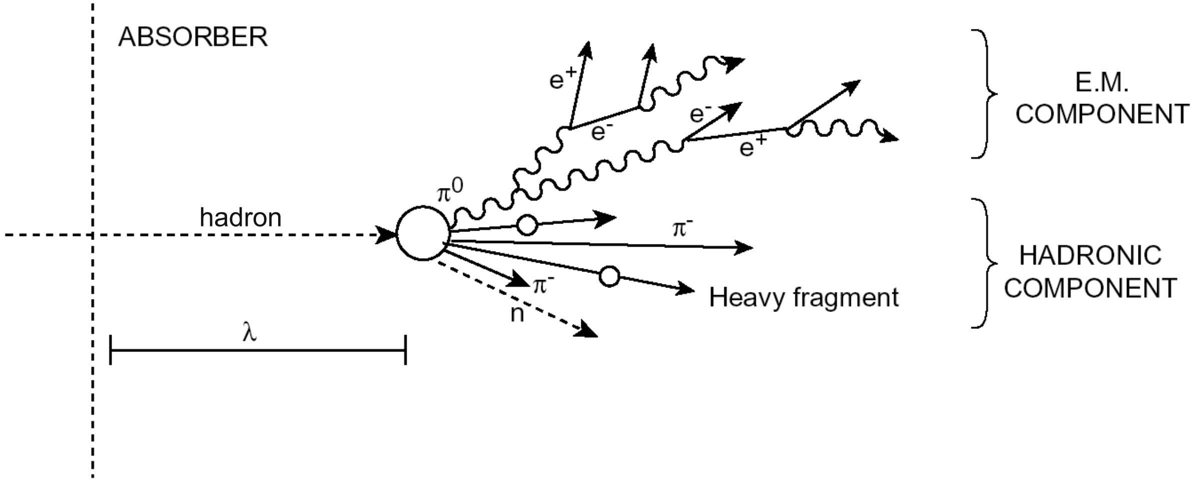


Technical details of the CALICE prototypes will be discussed in talks by Shu and Yong

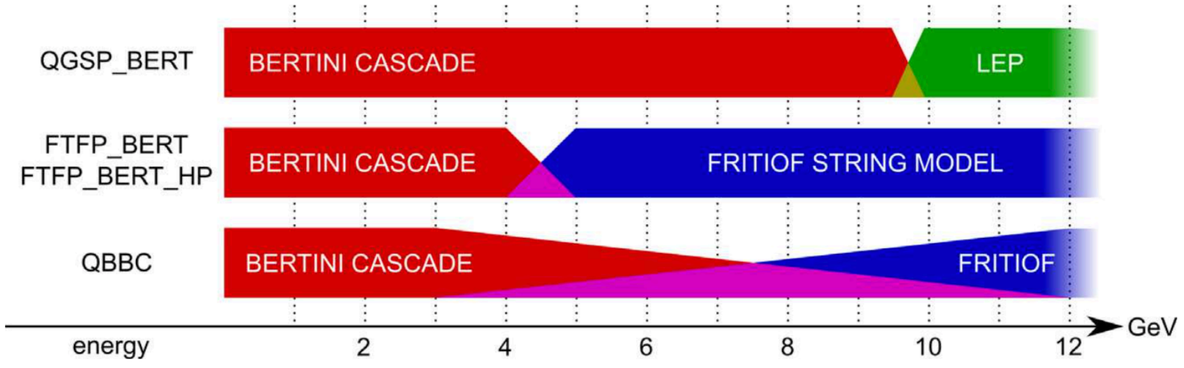
Hadronic showers

General properties and Monte Carlo modelling

- Hadronic shower development is rather complex:
  - Narrow EM core component from π^0/η
  - Surrounding halo dominated by charged hadrons
  - Large event-by-event fluctuation of EM/HAD ratio
  - Response to EM and HAD components is different in non-compensating calorimeters
  - Invisible energy as binding energy, nuclear recoil, neutrinos + late component
  - ➡ Limited hadronic energy resolution



- Geant4 hadronic shower modelling is not perfect
  - ➡ Strongly dependent on energy and absorber material
  - Validation of models using test beam data
- Some **results of studies on hadronic showers using test beam data with CALICE prototypes will be presented in this talk**

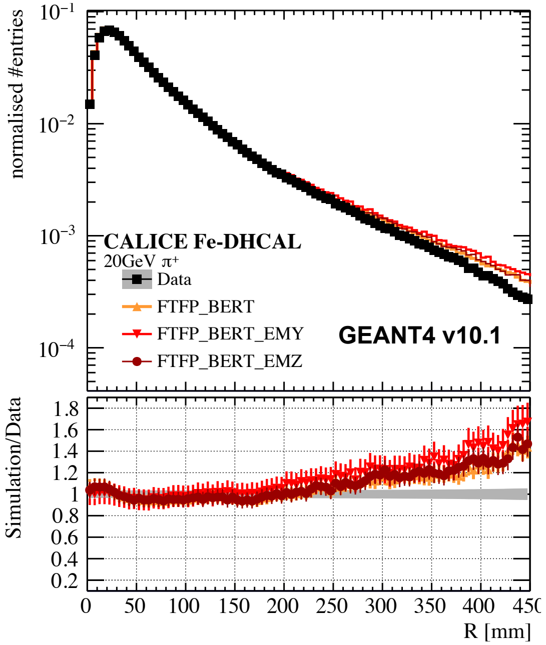


Hadronic shower profiles

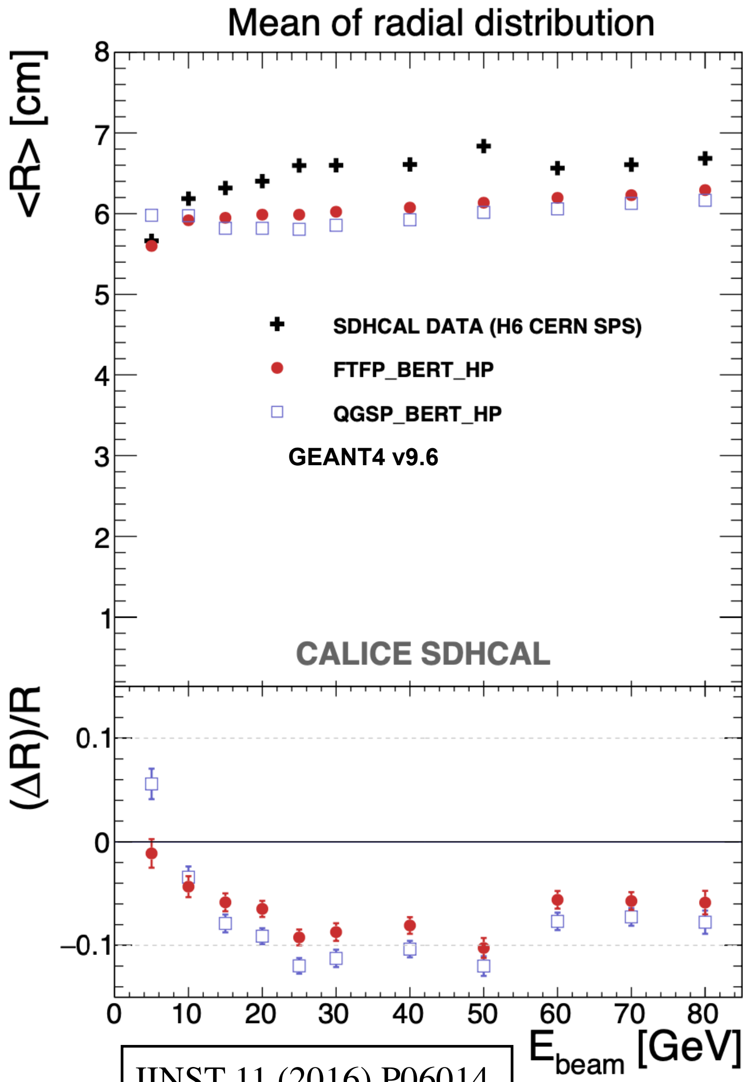
Radial development. Data-MC comparison is important for understanding of shower separation performance

- **Radial profile** (S)DHCAL: N_{hits} in 1-cm rings around shower axis

➡ Compare different physics lists with test beam data results



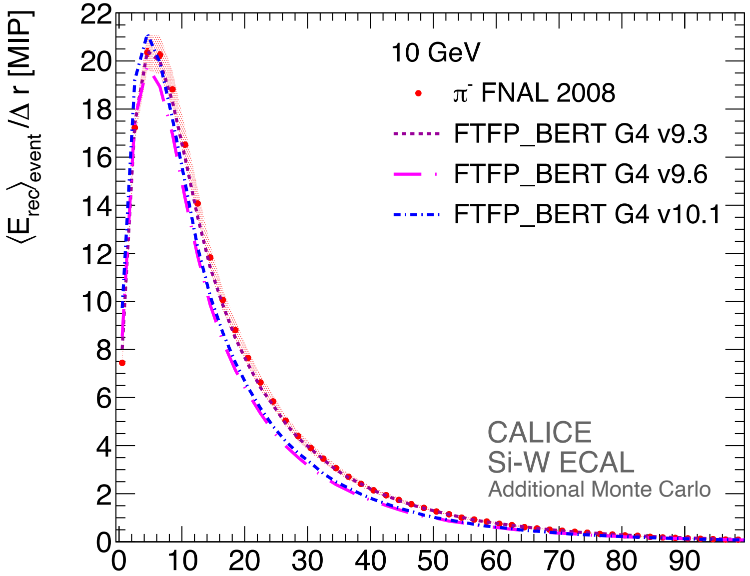
NIM A939 (2019) 89-105



JINST 11 (2016) P06014

- **Radial profile** Si-W ECAL: visible energy density in the cylinder of radius r and width Δr vs radial distance from shower axis

➡ Compare different Geant4 versions with test beam data results



NIM A794 (2015) 240-254

Radial distance [mm]

Hadronic shower profiles

Longitudinal development and decomposition of shower components

JINST 11 (2016) P06013

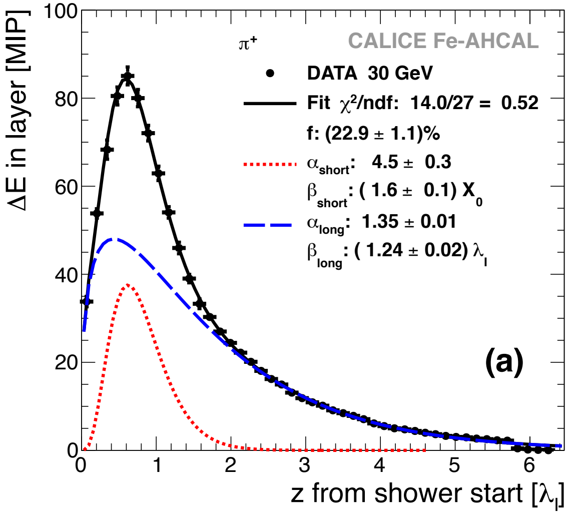
- **Longitudinal profile** (Fe-AHCAL): visible energy ΔE per transverse layer vs. longitudinal distance from the identified shower start
- Non-compensating calorimeters: Hadronic & electromagnetic response not the same (h/e < 1)
- Parametrisation:

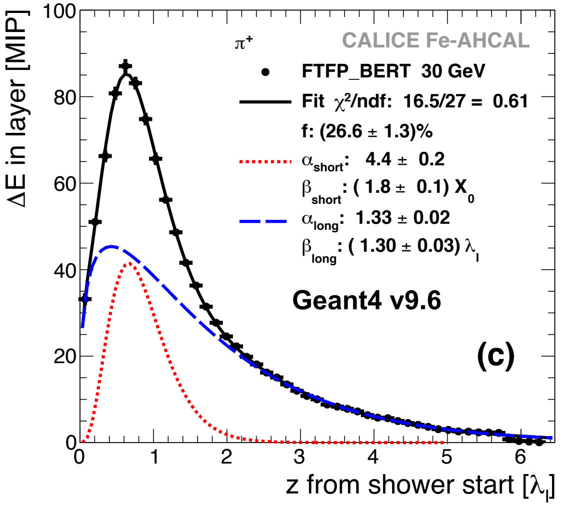
$$\Delta E = A\left\{\frac{f\cdot\exp\left(-\frac{z}{\beta_{short}}\right)}{\beta_{short}\cdot\Gamma(\alpha_{short})}\cdot\left(\frac{z}{\beta_{short}}\right)^{\alpha_{short}-1}+\frac{(1-f)\cdot\exp\left(-\frac{z}{\beta_{long}}\right)}{\beta_{long}\cdot\Gamma(\alpha_{long})}\cdot\left(\frac{z}{\beta_{long}}\right)^{\alpha_{long}-1}\right\}$$

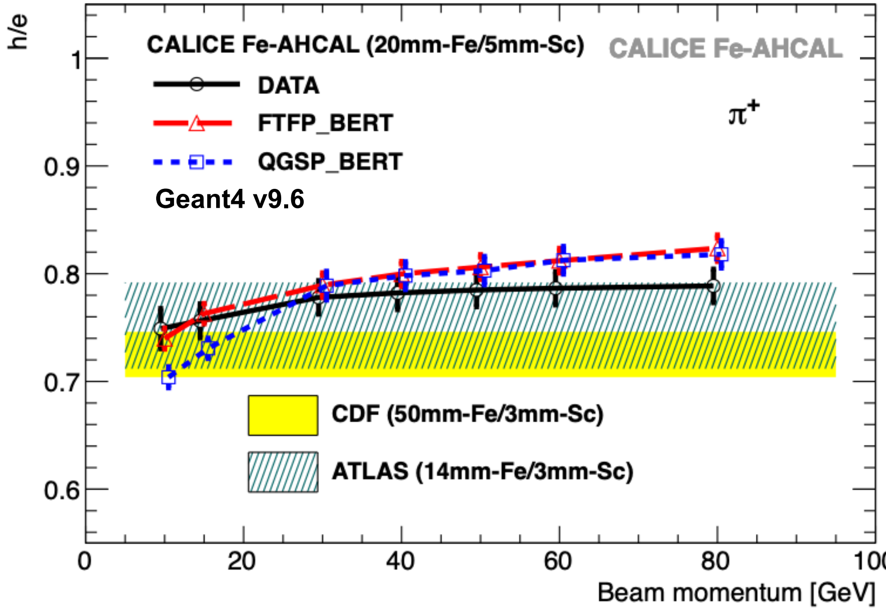
proposed in R.K. Bock et al. NIM, 186 (1981)

A - scaling factor
f - fraction of the "short" component
Γ - gamma function

z - distance from shower start
αshort and ***αlong*** - shape parameters
βshort < ***βlong*** - slope parameters





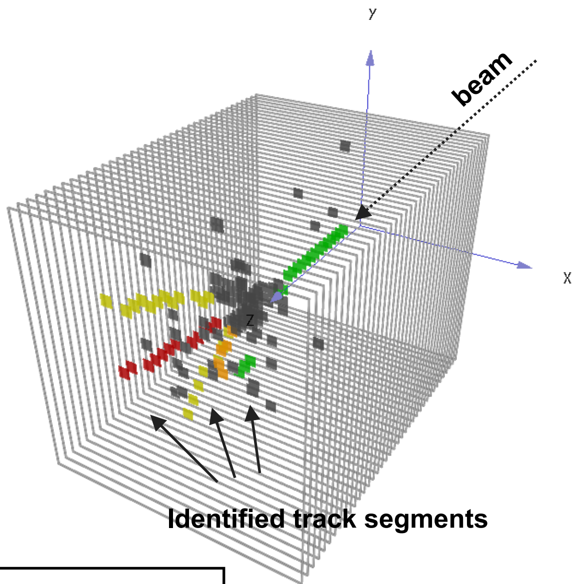


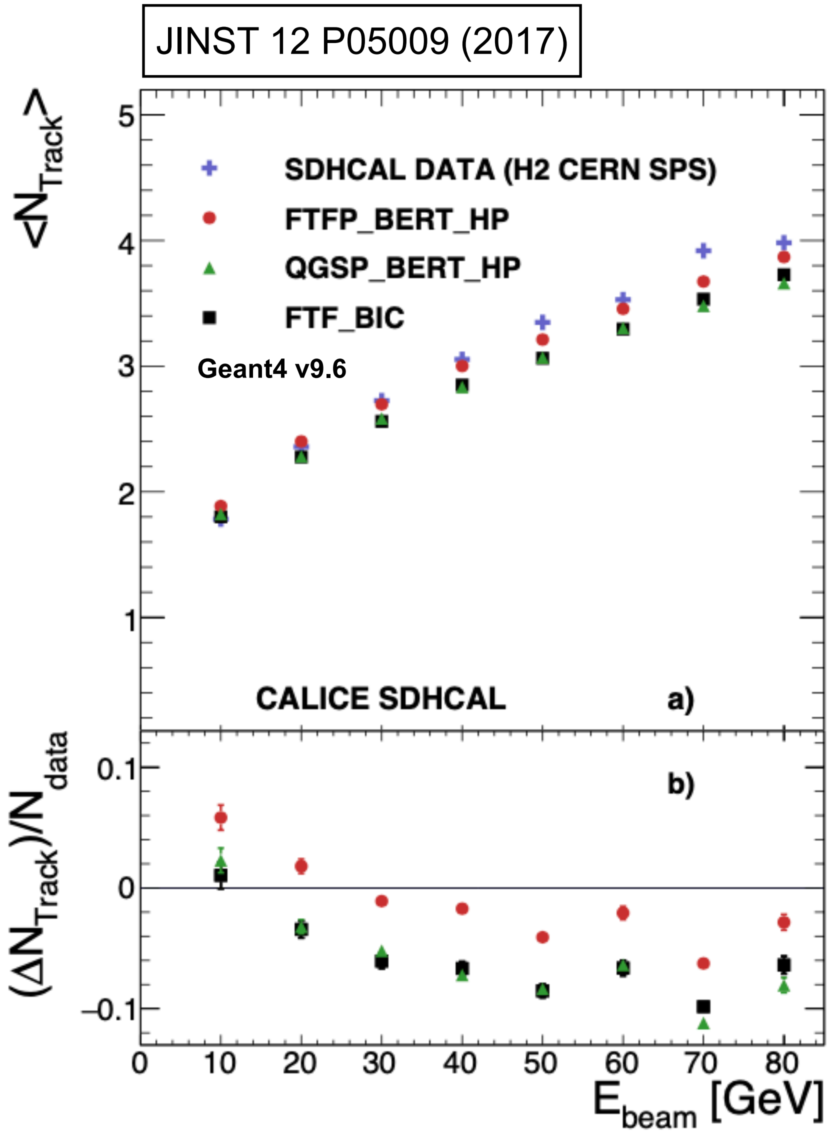
➡ Extract h/e ratio and compare to GEANT4 v9.6 simulations

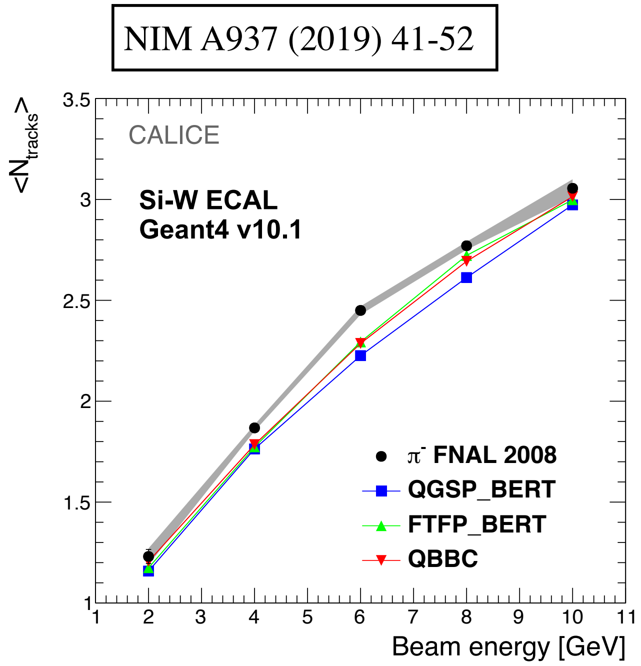
Track segments

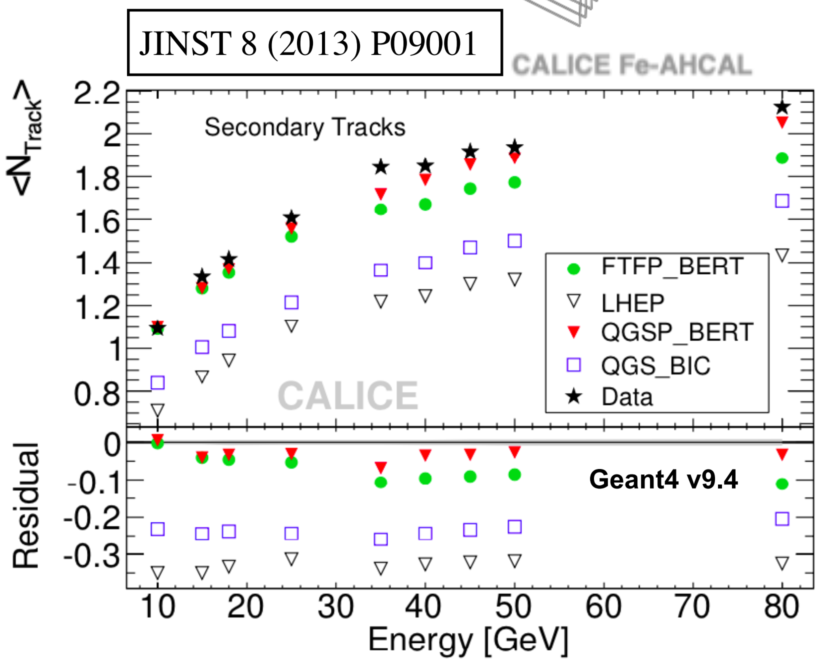
In hadronic showers

- Track finding within shower sub-structure works in all high granularity technologies
- Useful for detailed study of shower development (data vs. simulation), calibration and event characterisation









Particle Identification

Multi-Variate Analysis with SDHCAL and AHCAL

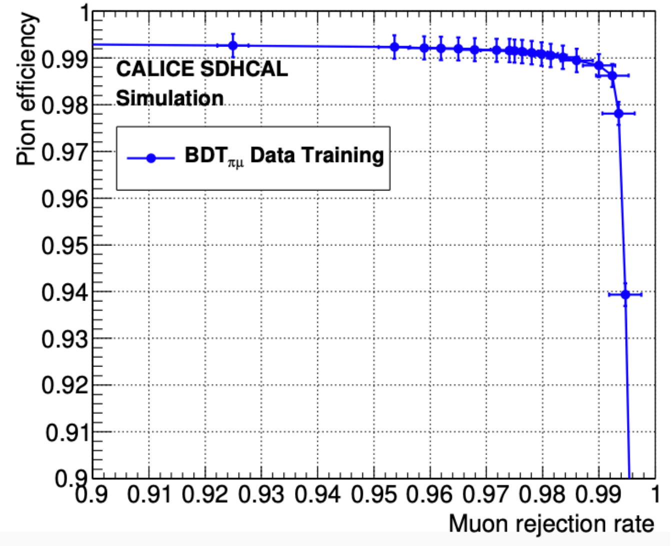
JINST 15 (2020) 10, P10009

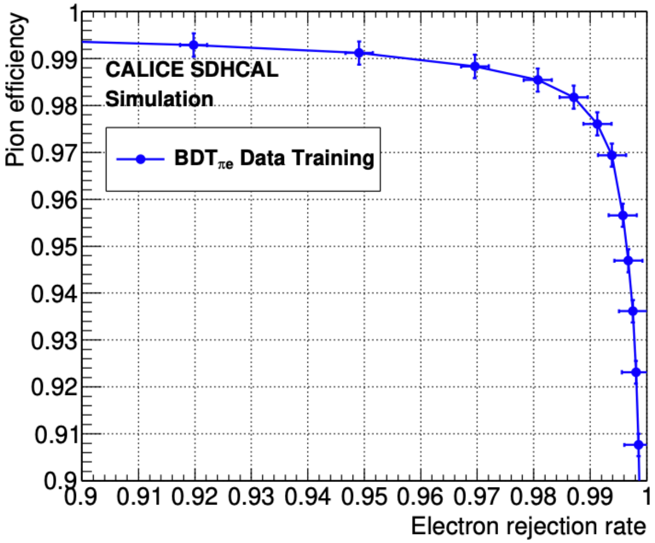
- Discriminating variables based on event topologies of **hadrons**, **electrons** and **muons** are used to train a Boosted Decision Tree (BDT) classification model

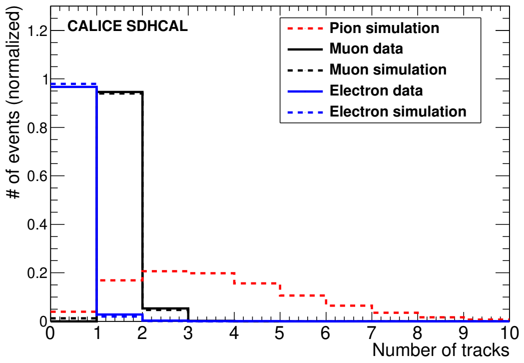
  SDHCAL:

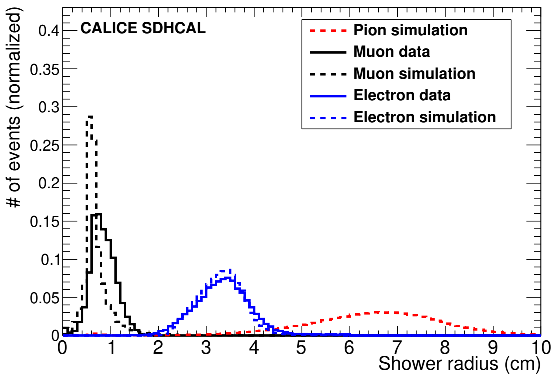
  - Shower start layer number
  - Number of track segments
  - Ratio of shower layers over total number of layers
  - Shower density
  - Shower radius
  - Shower maximum position (longitudinal coordinate)
- Training on both MC and data (SDHCAL)

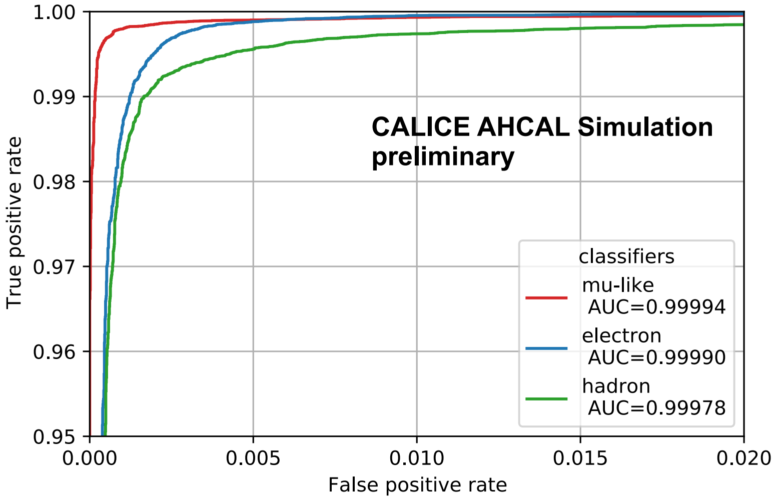
➡ High signal purity/efficiency obtained











$$TPR = \frac{TP}{TP + FN}$$

$$FPR = \frac{FP}{FP + TN}$$

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  SDHCAL:

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  - Shower density
  - Shower radius
  - Shower maximum position (longitudinal coordinate)
- Training on both MC and data (SDHCAL)

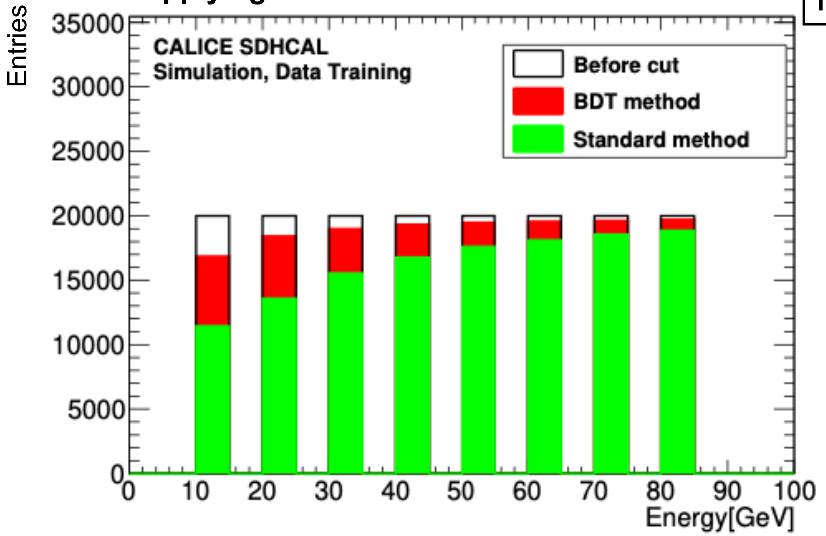
➡ High signal purity/efficiency obtained

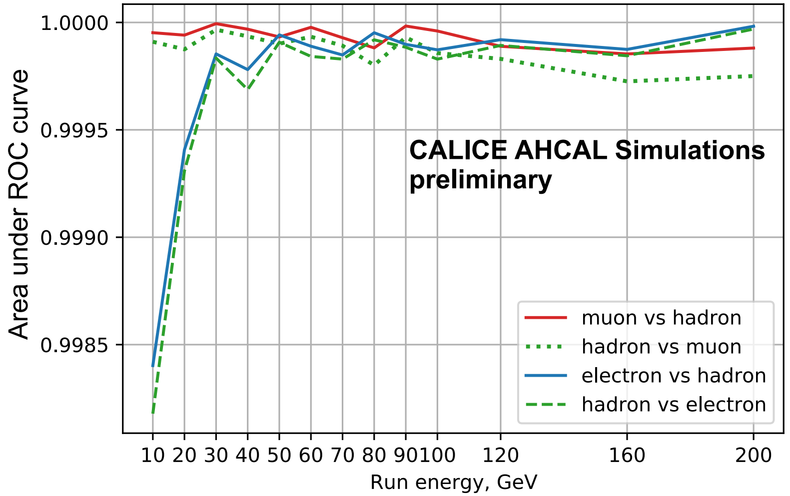
➡ Stable performance on wide energy range (slight decrease for low energies)

More examples for ongoing multivariate analyses with AHCAL in backup slides

JINST 15 (2020) 10, P10009

Simulated pion events before and after applying selection methods

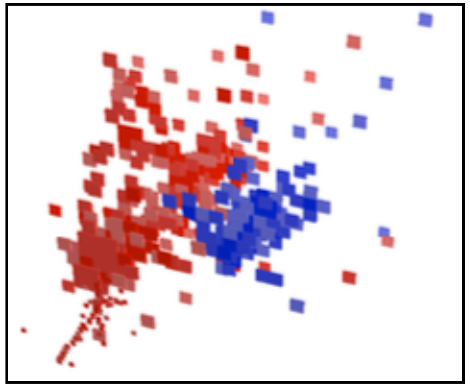




Particle Flow Algorithms applied to CALICE prototype data

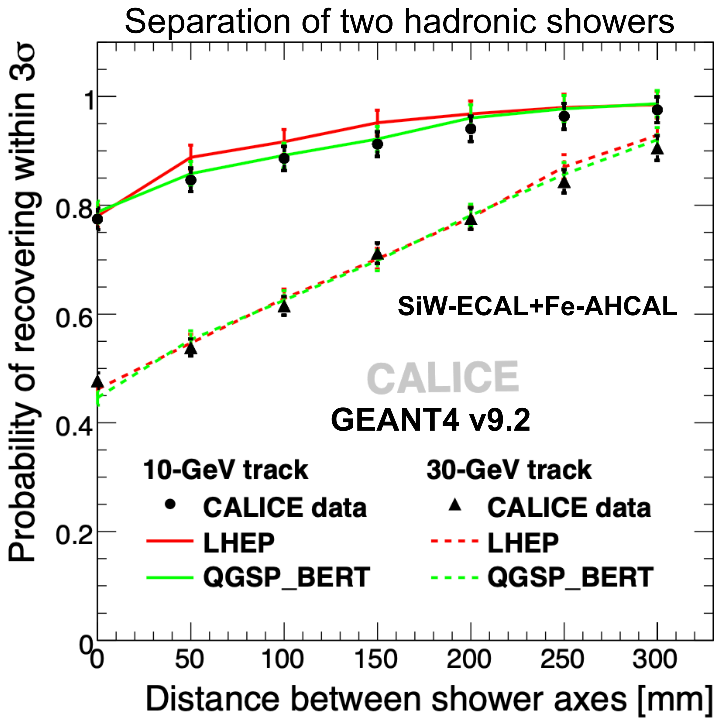
Two particle separation performance

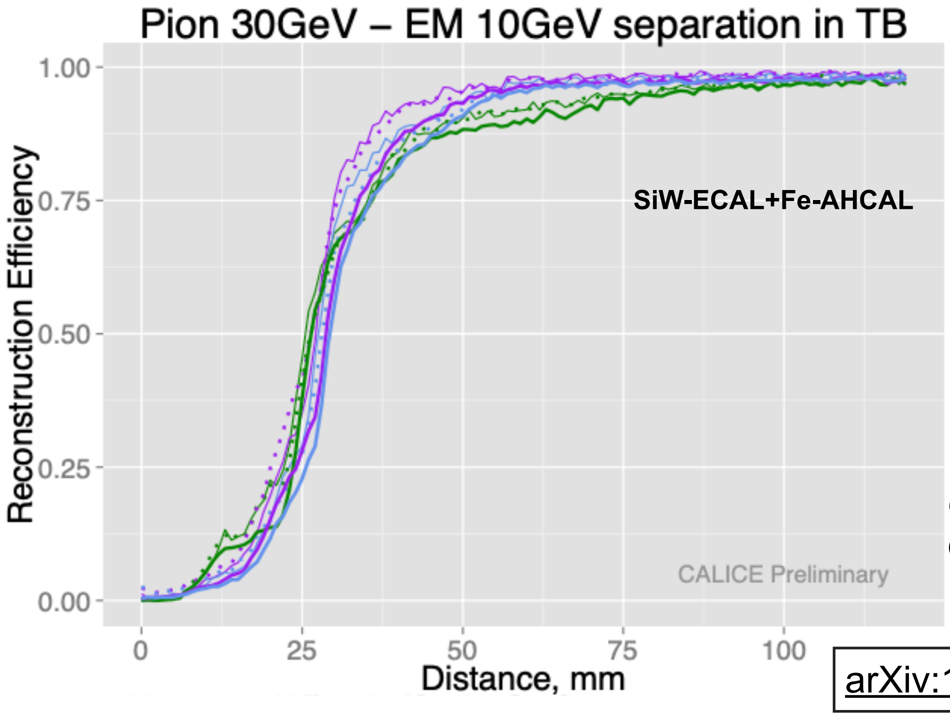
- Figure of merit for Particle Flow algorithms
    - Artificially overlaid test beam events in SiW ECAL + AHCAL
    - used to tune PFA parameters
    - ➡ Good agreement between data and simulations



Neutral Hadron
Charged Hadron

JINST 6 P07005 (2011)





GEANT4 v10.1
QGSP_BERT

arXiv:1802.00672

Energy reconstruction

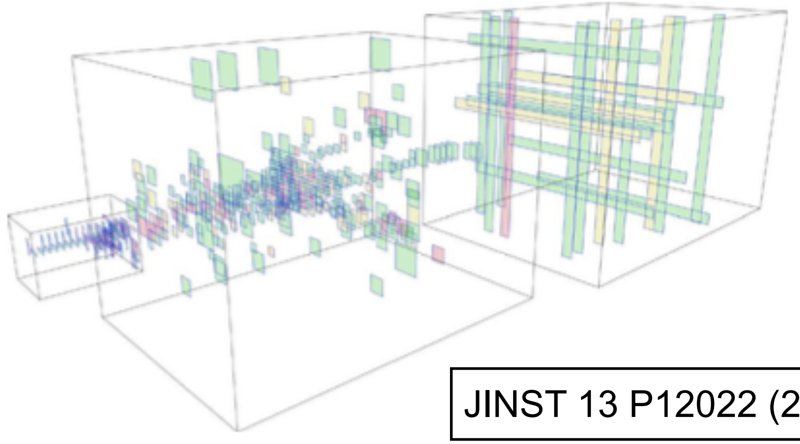
Analog readout

Software compensation method

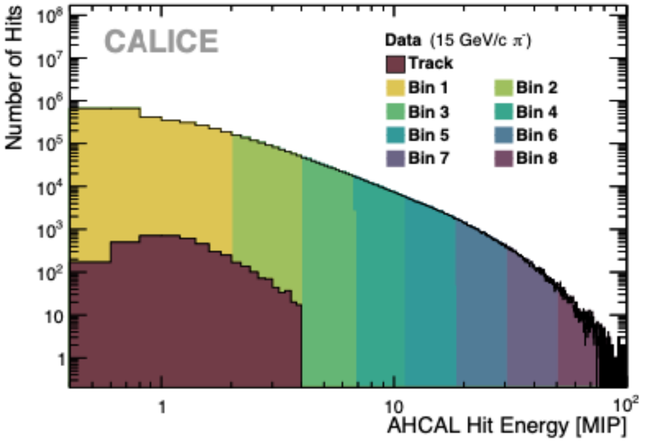
- h/e response compensation by assigning energy-dependent weights to hit energies (⇒local energy density)
  - Higher weights for **low energy hits** - dominated by **HAD** component
  - Lower weights for **high energy hits** - dominated by **EM** component

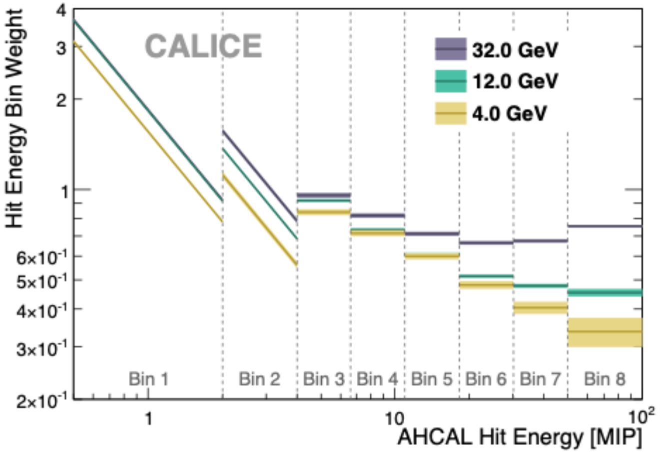
➡ Significant energy resolution improvement 10-20%

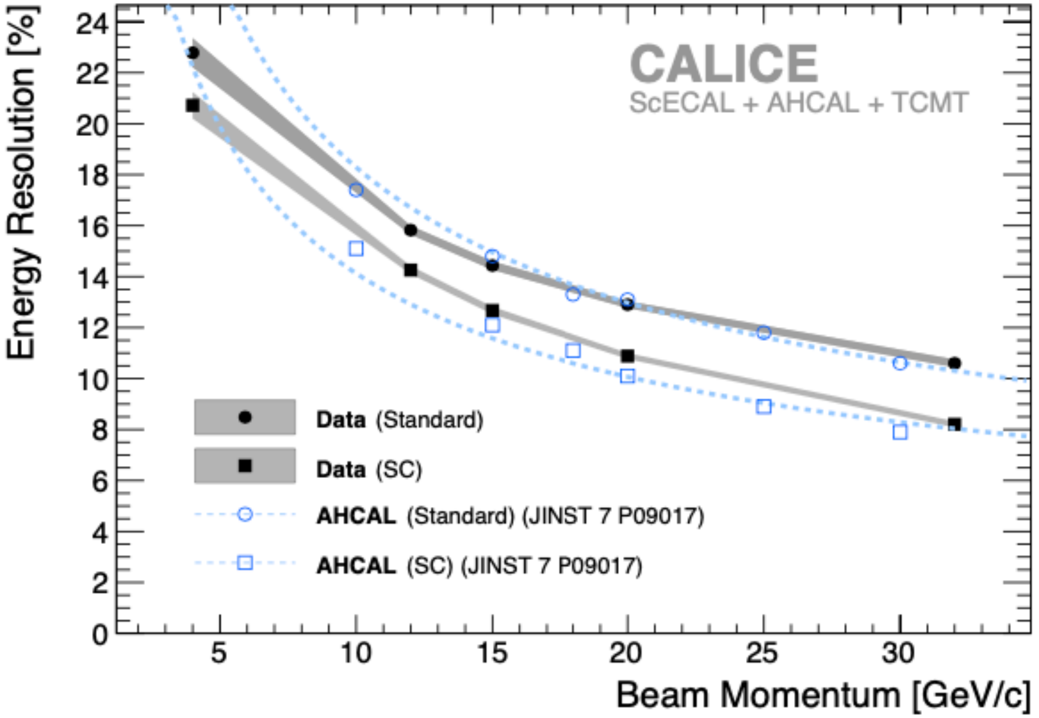
➡ System performance ScECAL+AHCAL+TCMT is similar to AHCAL alone



JINST 13 P12022 (2018)







Energy reconstruction

Semi-digital readout

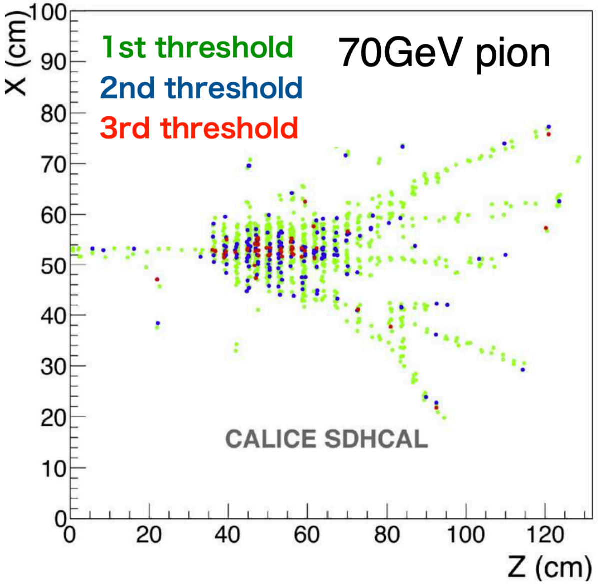
JINST 11 P04001 (2016)

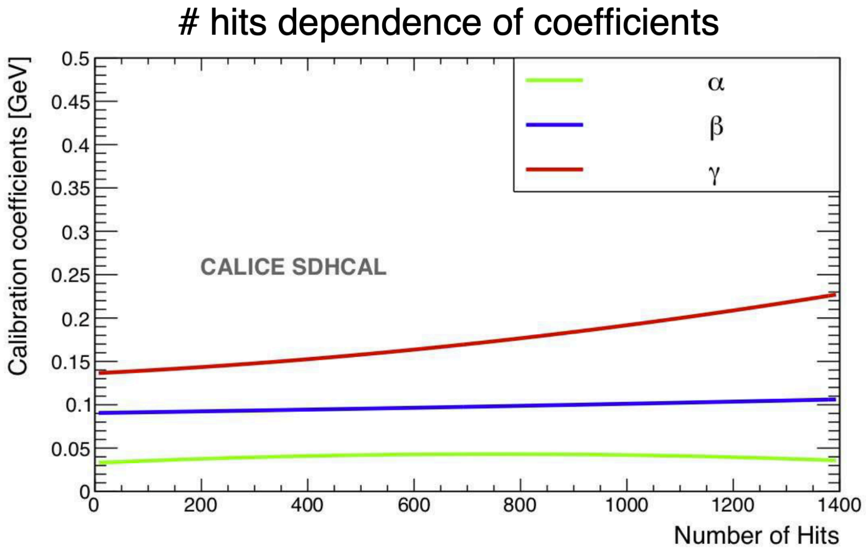
Multi-threshold reconstruction method:

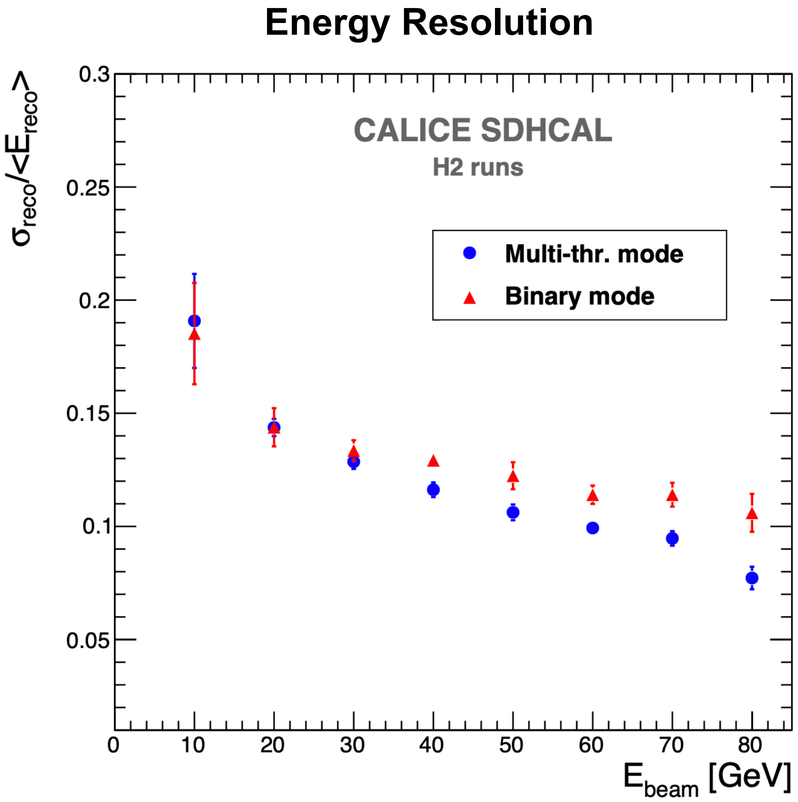
- N_1,N_2,N_3: Exclusive number of hits corresponding to 1st, 2nd and 3rd charge thresholds
- α, β, γ: weights, quadratically dependent on total number of hits, parameters for each curve are extracted from test beam data @ SPS CERN

➡ Saturation effect at high energy region is mitigated

$$E_{\text{reco}} = \alpha N_1 + \beta N_2 + \gamma N_3$$







Timing

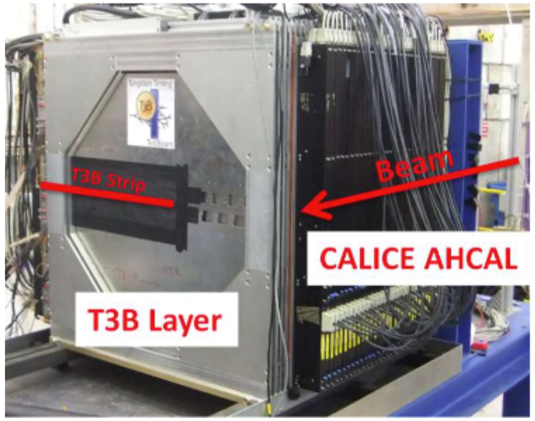
Towards 5D calorimetry

- **CALICE T3B**: Setup of 15 scintillator-SiPM channels with **high time resolution** placed behind W-AHCAL/Fe-SDHCAL

➡ good agreement with GEANT4 v9.4 with emphasis on HP package for tungsten

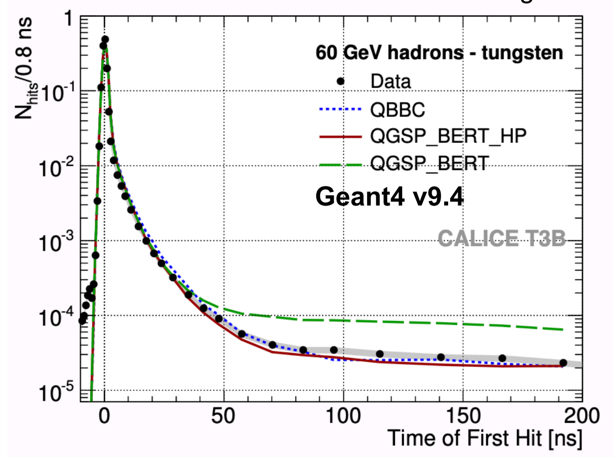
➡ higher fraction of late component with tungsten specifically for low hit energies (late neutrons)

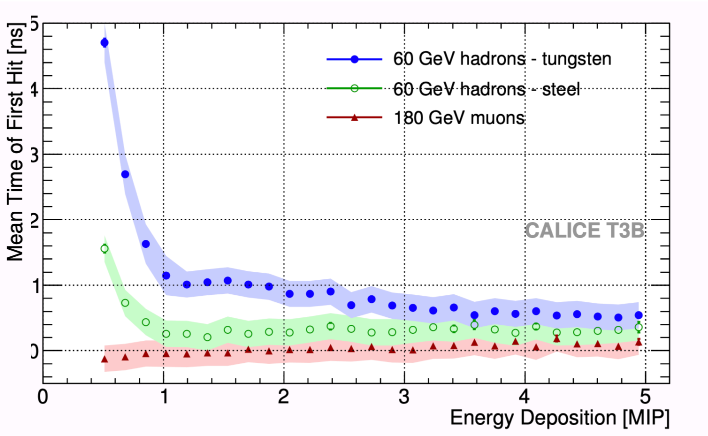
➡ relevant time scale ~1ns



JINST 9 P07022 (2014)

Timing of hadronic showers





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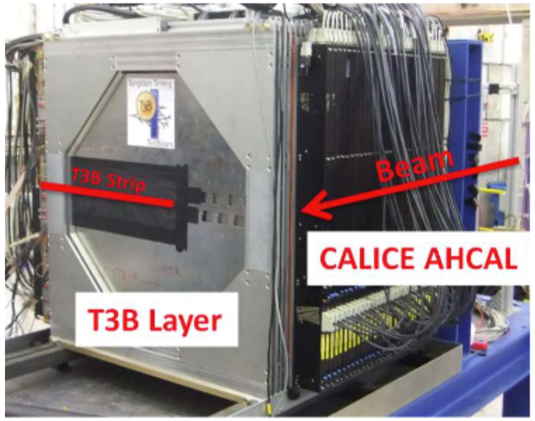


JINST 9 P07022 (2014)

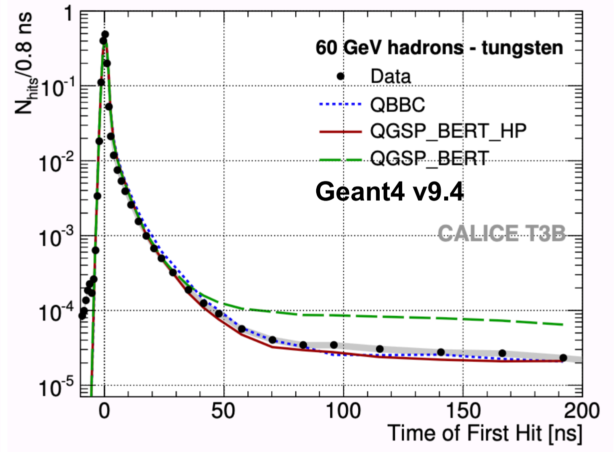
- **AHCAL**: Hit time measurement capability with technological prototype

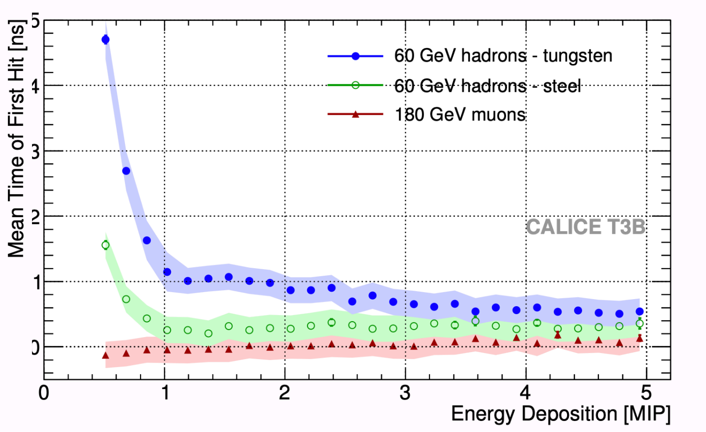
➡ Intrinsic single channel hit time resolution of ~1ns for muons

➡ Further optimisation and analysis on hadrons in progress

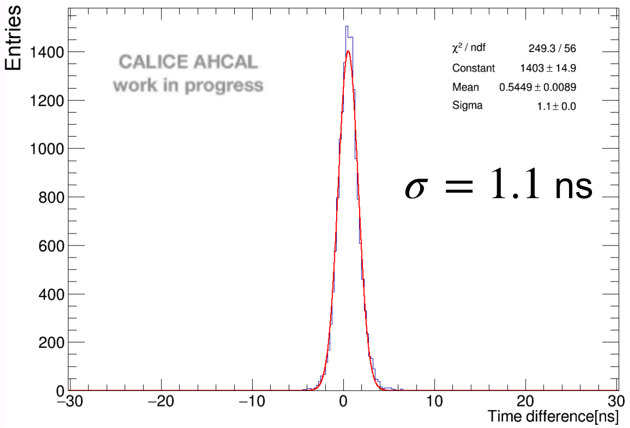
➡ Envisage study of dynamical developments of showers

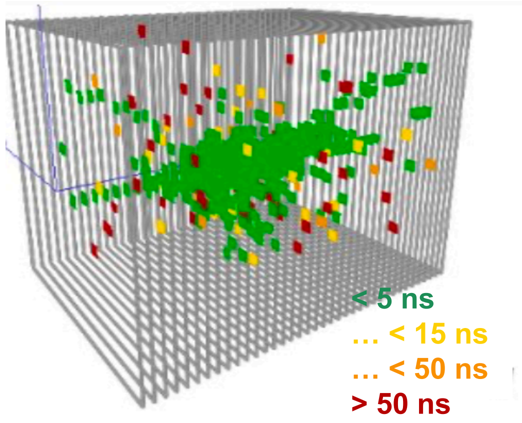
Timing of hadronic showers





Hit time difference distribution for muon hits in two consecutive AHCAL channels





Summary & Outlook

- High granularity of calorimeters is one of the key components to reach the unprecedented jet energy resolution at future lepton colliders
- Imaging capabilities of CALICE highly granular calorimeter prototypes provide excellent opportunity to study hadronic showers at beam tests
  - Detailed hadronic shower structure analysis
  - Validation of Geant4 modelling and feedback to developers
  - Calorimeter-based particle identification
  - PFA performance tests on test beam data and feedback to developers
  - Improving hadronic energy resolution using software compensation and multi-threshold reconstruction
- Timing measurements show promising results ⇒ next step towards 5D calorimetry
- Analyses with the CALICE technological prototypes are ongoing - stay tuned

Backup

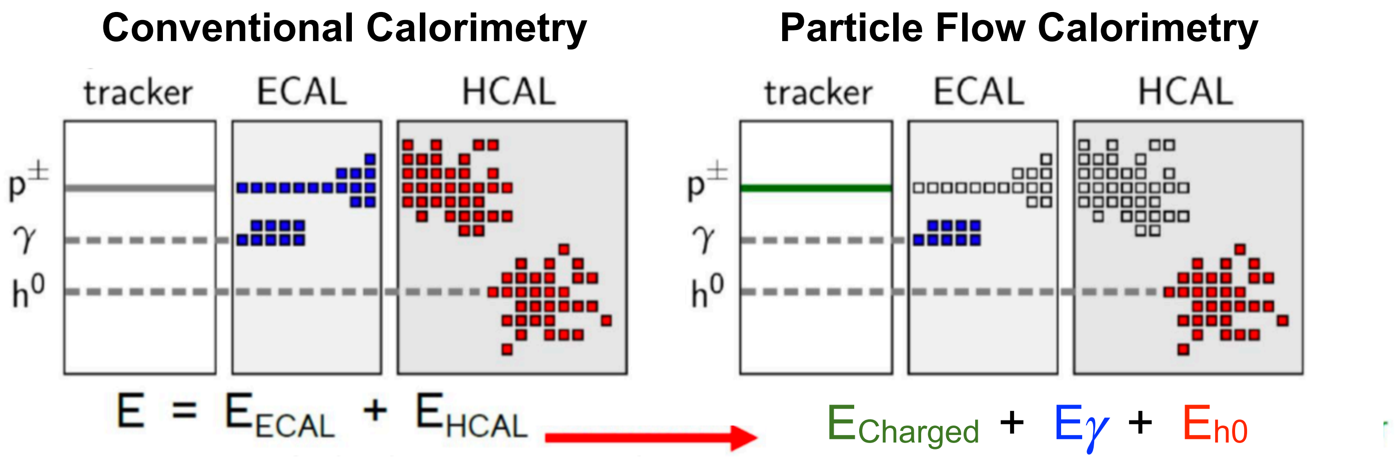
Particle Flow Calorimetry

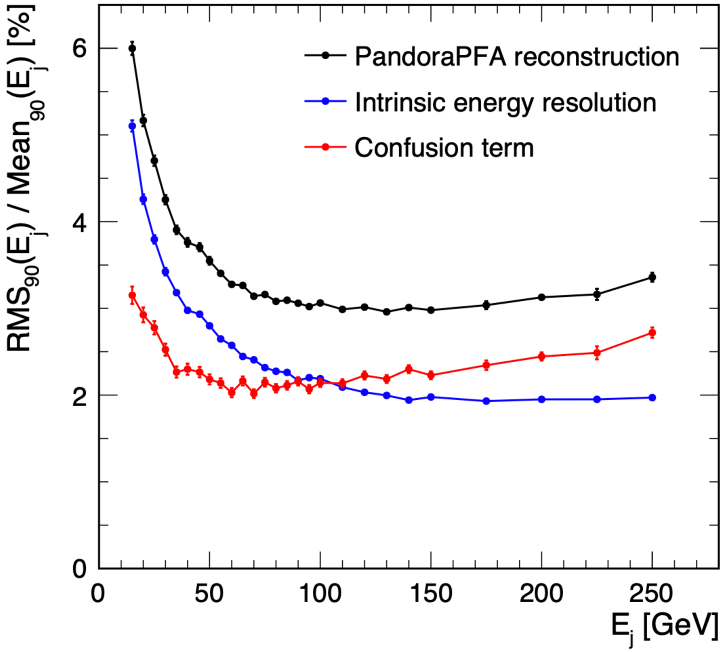
Reaching the Highest Precision

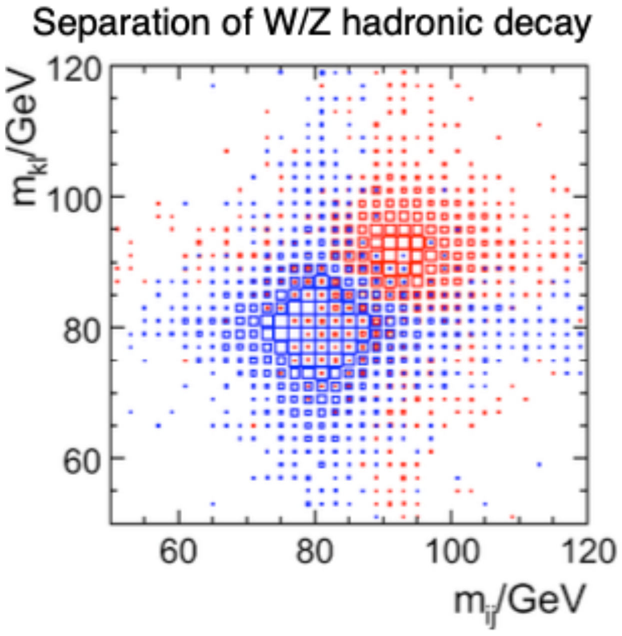
- At future e^+e^- collider experiments: Unprecedented jet energy resolutions for precise physics with jets required

➡ Use Particle Flow Algorithms (PFA)

  - Measurement of sub-detector providing the best resolution on particle-by-particle basis
    - ➡ Charged particles: Tracker
    - ➡ Photons: ECAL
    - ➡ Neutral hadrons: ECAL+HCAL
  - Requirements for PFA :
    - ➡ High precision tracker
    - ➡ **High granularity calorimeters**







Goal: 3-4% jet energy resolutions!

Single Particle Energy Resolution

Performance of CALICE Calorimeter Prototypes - Examples

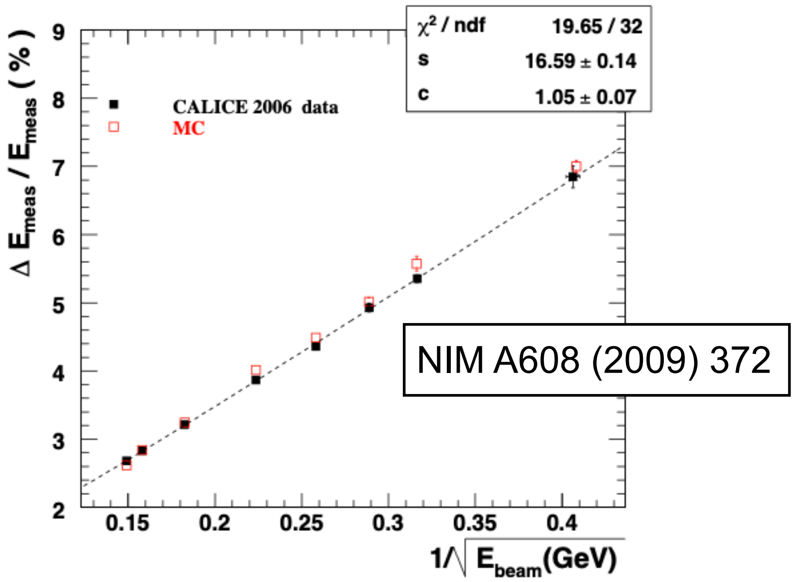
- Achieved single particle (intrinsic) energy resolution of CALICE calorimeter prototypes remarkable - even if they are not explicitly optimised on this quantity alone

➡ SiW ECAL physics prototype (EM):
~16.6% / $\sqrt{E(GeV)}$ ⊕ ~1.05%

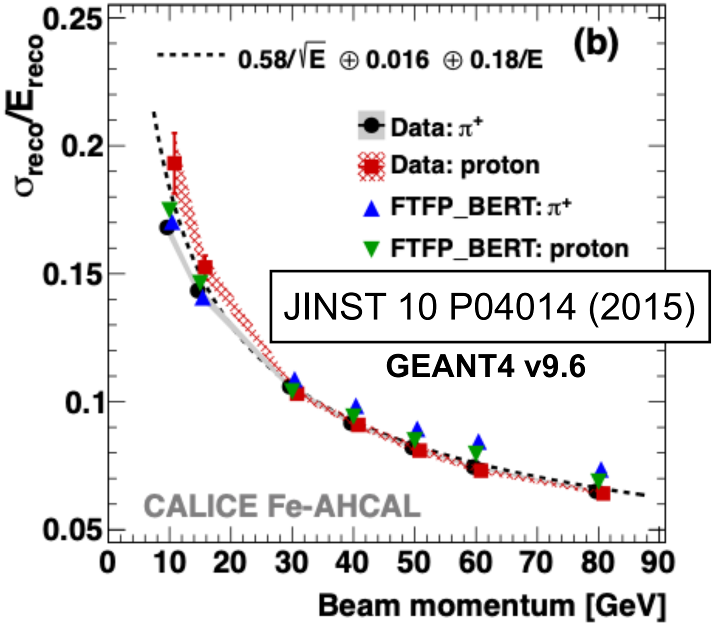
➡ ScECAL physics prototype (EM):
~12.5% / $\sqrt{E(GeV)}$ ⊕ ~1.2%

➡ AHCAL physics prototype (HAD):
~58% / $\sqrt{E(GeV)}$ ⊕ ~1.6%
(before weighting)

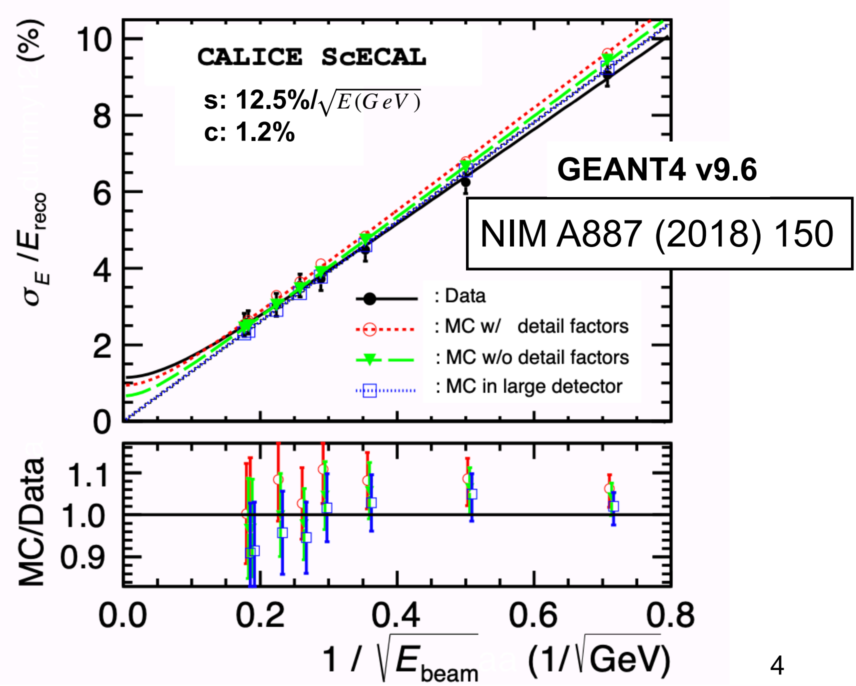
Energy Resolution SiW ECAL (e⁻)



Energy Resolution AHCAL (pi⁺/protons)

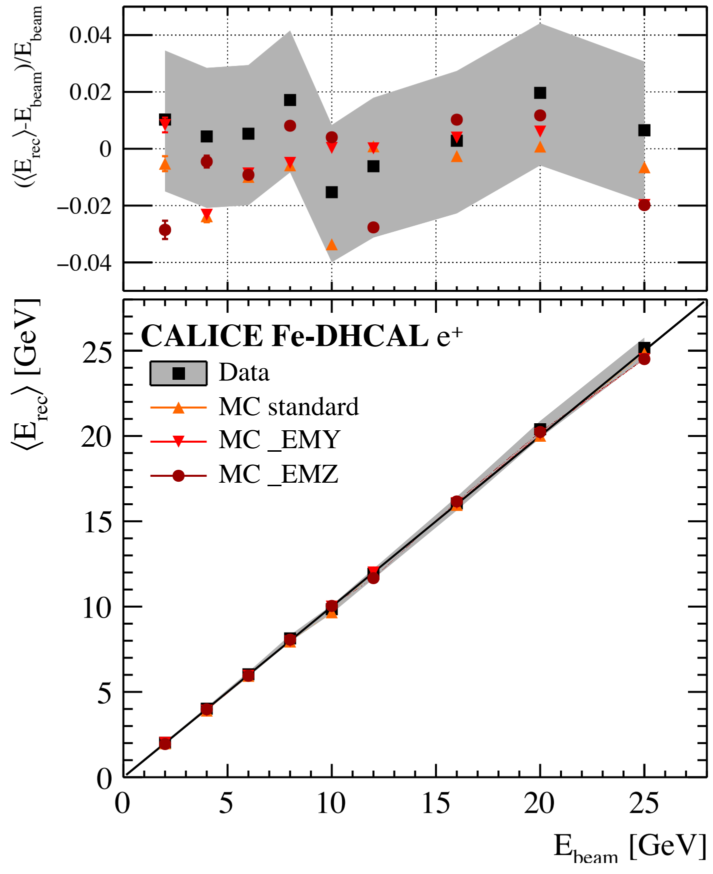


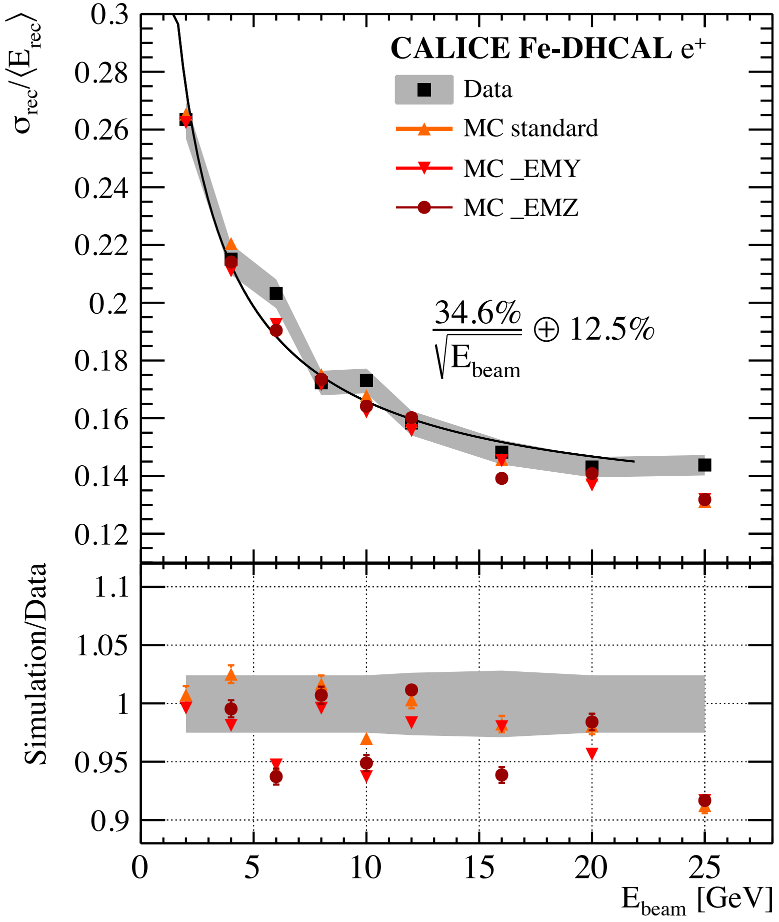
Energy Resolution ScECAL (e⁻)



Digital hadronic calorimeter (DHCAL)

Linearity and resolution

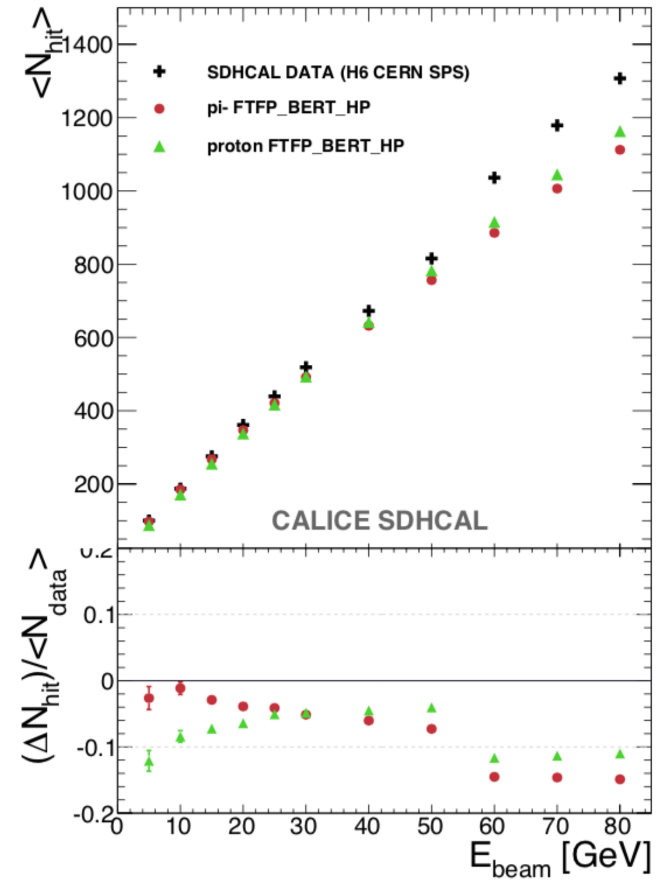


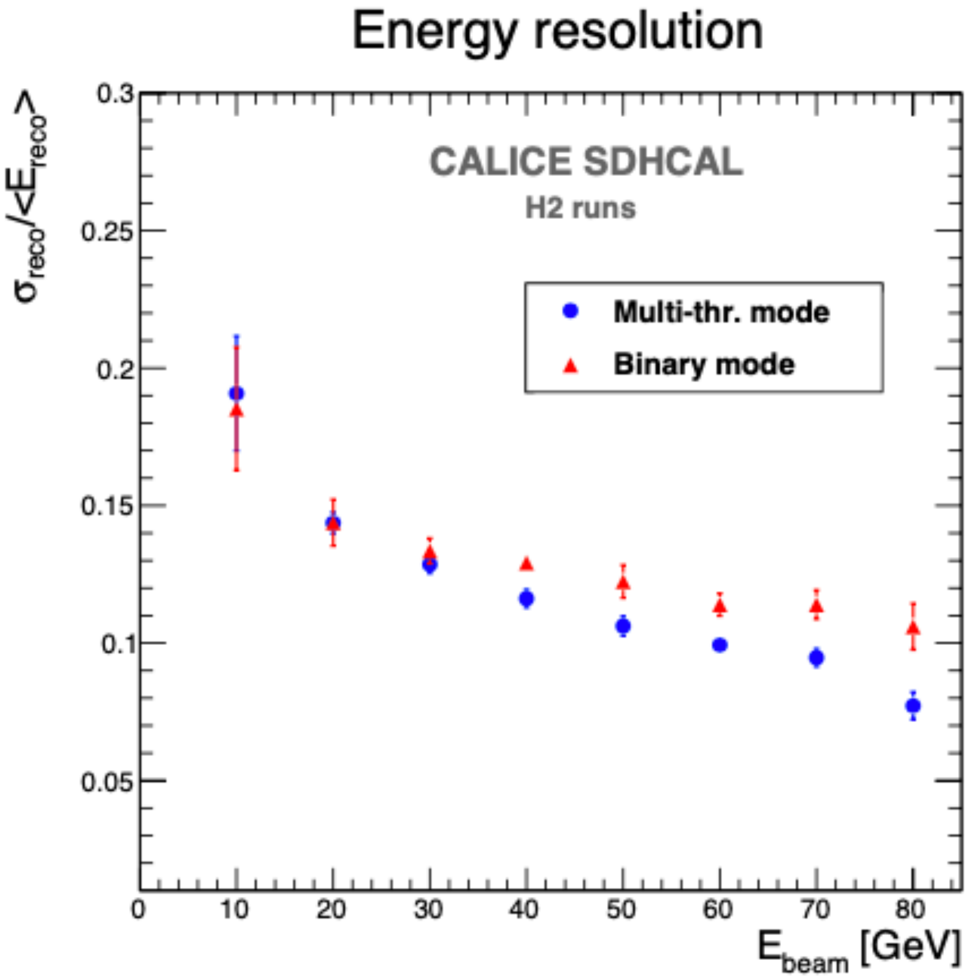


NIM A939 (2019) 89-105

Semi-Digital Hadronic Calorimeter (SDHCAL)

Linearity and resolution

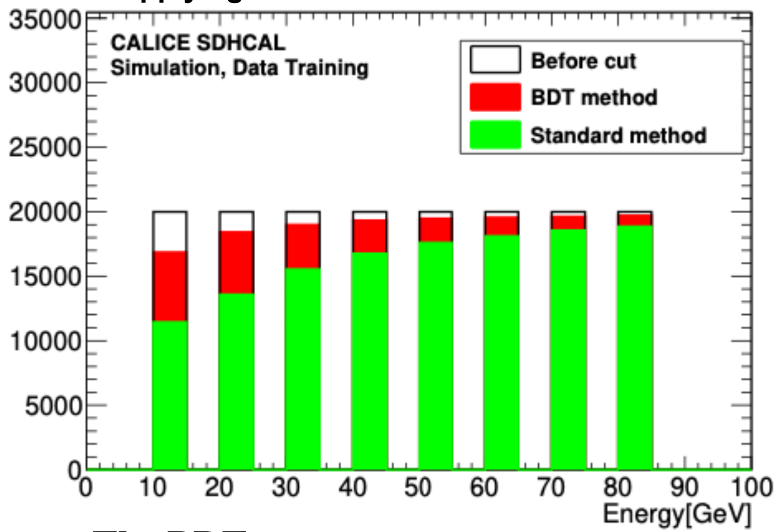


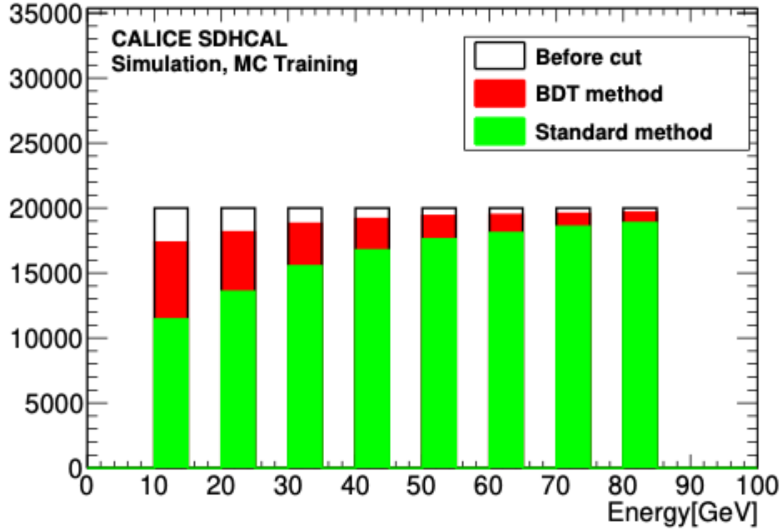


JINST 11 (2016) P06014

BDT classification SDHCAL

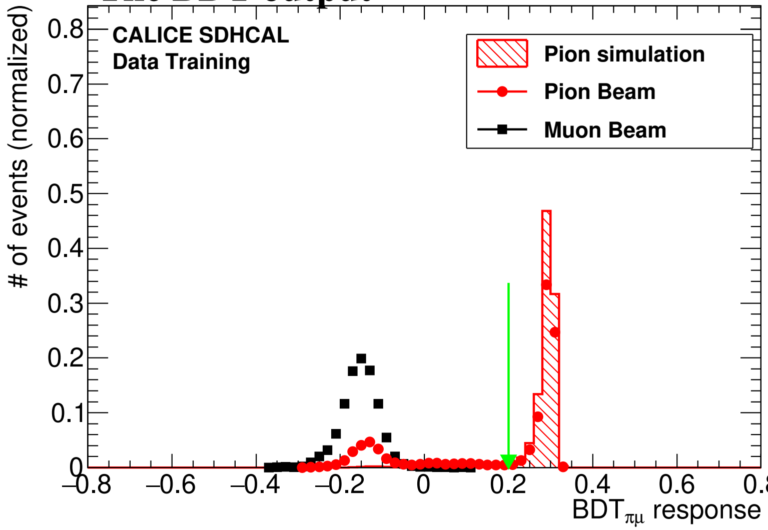
Simulated pion events before and after applying selection methods

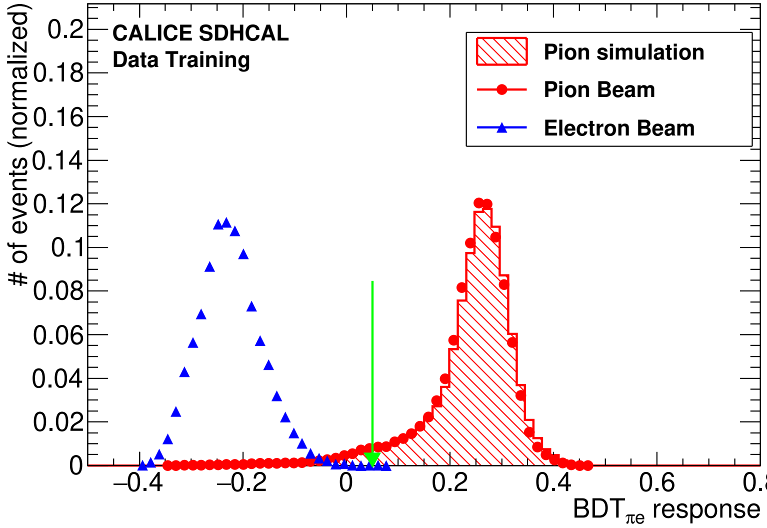




JINST 15 (2020) 10, P10009

The BDT output





BDT classification AHCAL

Model and input.

Software and model:

- **LightGBM** package
- Multi-class **Gradient Boosted Decision Tree**
- **Multi-log/BCE** loss function
- Output**: 3 probabilistic classifiers** (electron, hadron, muon-like)

Training and test set:

- **MC** particles **10-200GeV** simulated using *Geant4 (v10.03.p02)* QGSP_BERT_HP physics list:
  - **pions (st ≤ 40)**
  - **electrons**
  - **muons**
- Simulated data is split **50/50 - test/train**
- Simultaneous training on whole energy range

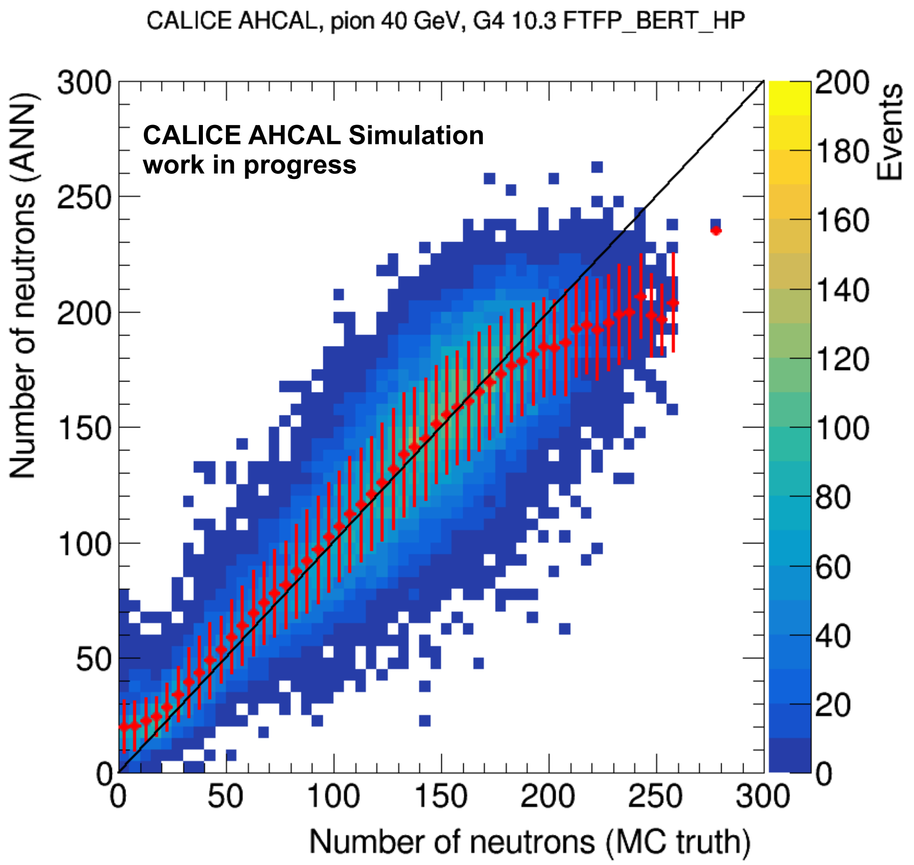
Observables (sorted by importance):

- Event radius
- Shower start layer number
- Energy fraction in shower core
- Energy fraction in shower central region (in XY plane)
- Mean hit energy after shower start
- Energy fraction in first 22 layers
- Number of hits
- Center of gravity in z
- Number of track hits
- Number of layers with hits from last 5
- Number of hits after shower start

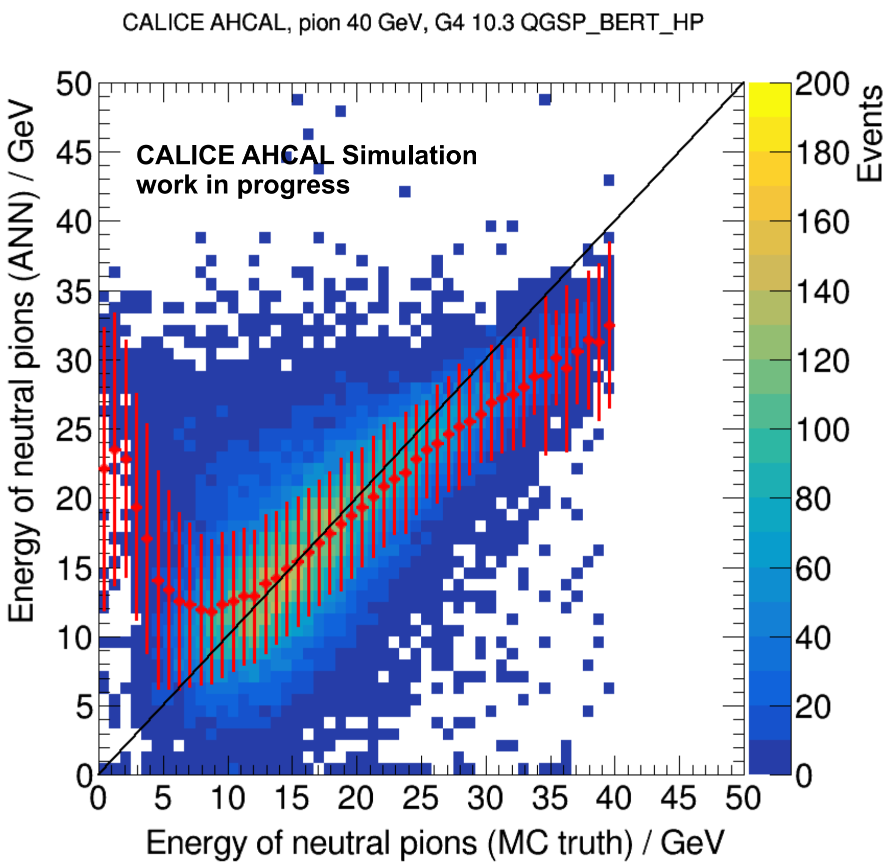
Ongoing MVA examples with AHCAL

DNN based prediction of hadronic shower properties using global observables

- Prediction vs MC truth for number of neutrons



- Prediction vs MC truth for energy of neutral pions



More details can be found in Marina's ILCX 2021 presentation

Ongoing MVA examples with AHCAL

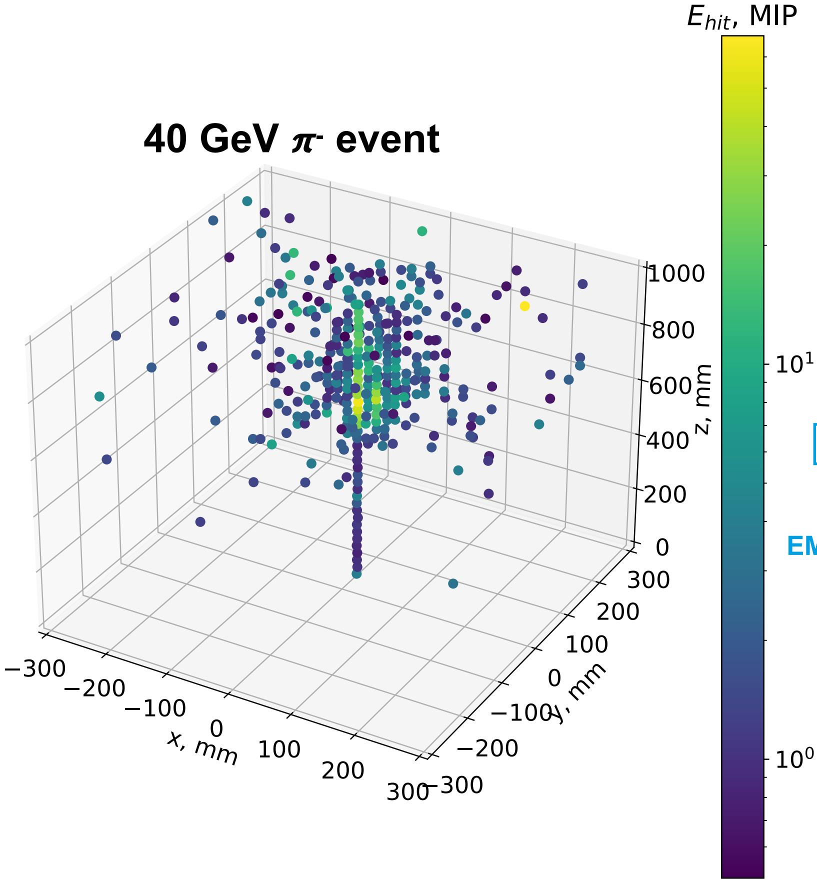
GNN based reconstruction of hadronic shower components

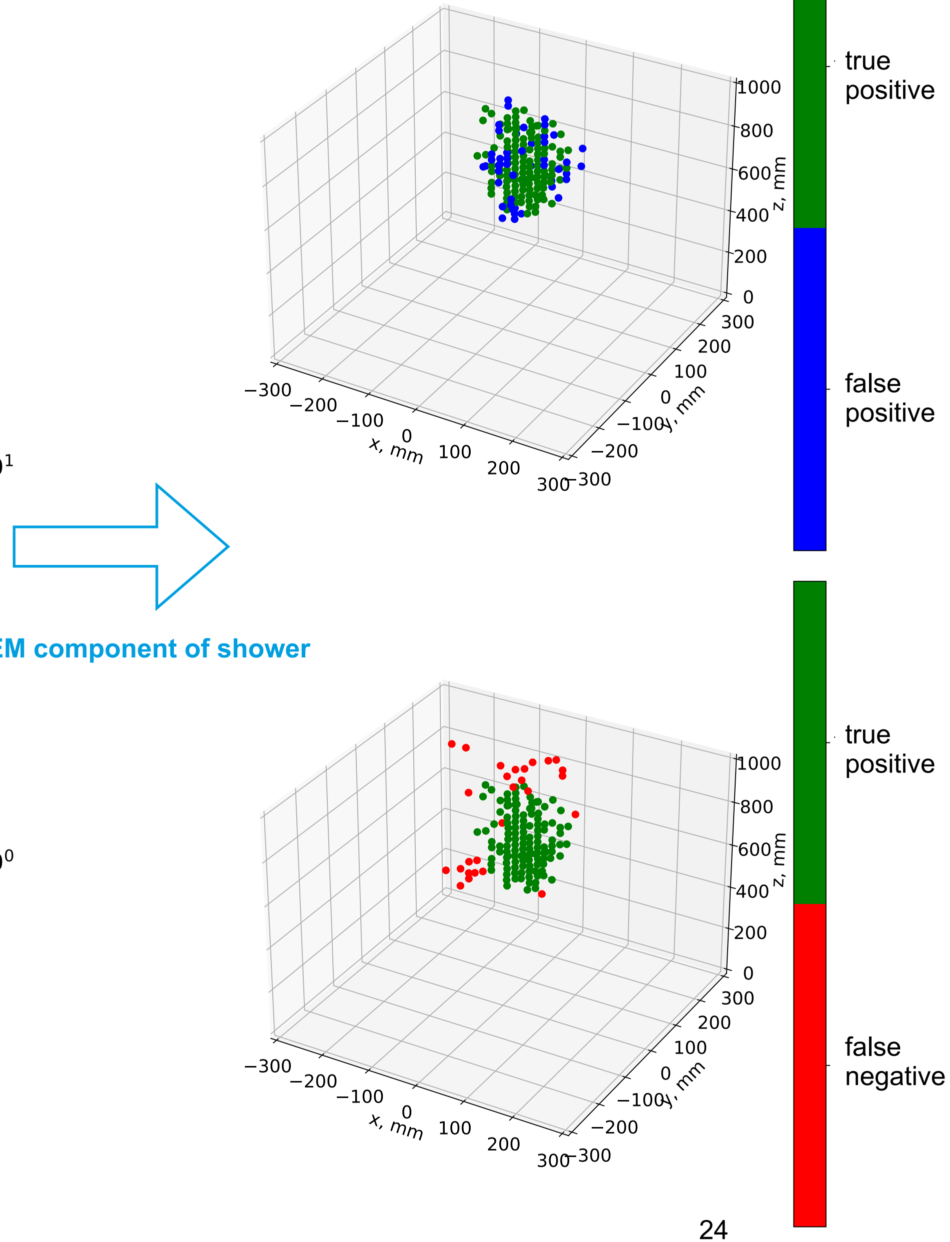
Graph representation of calorimeter event:

- Nodes - hits
- Node features - position, energy, (time)
  - — Edges - neighbours (R < Rmax)
  - — Edge weights - 1 if pair of nodes belong to same **fundamental object** (e/m sub-shower, track), otherwise 0

Graph neural network is trained to predict edge weights

40 GeV π^- event





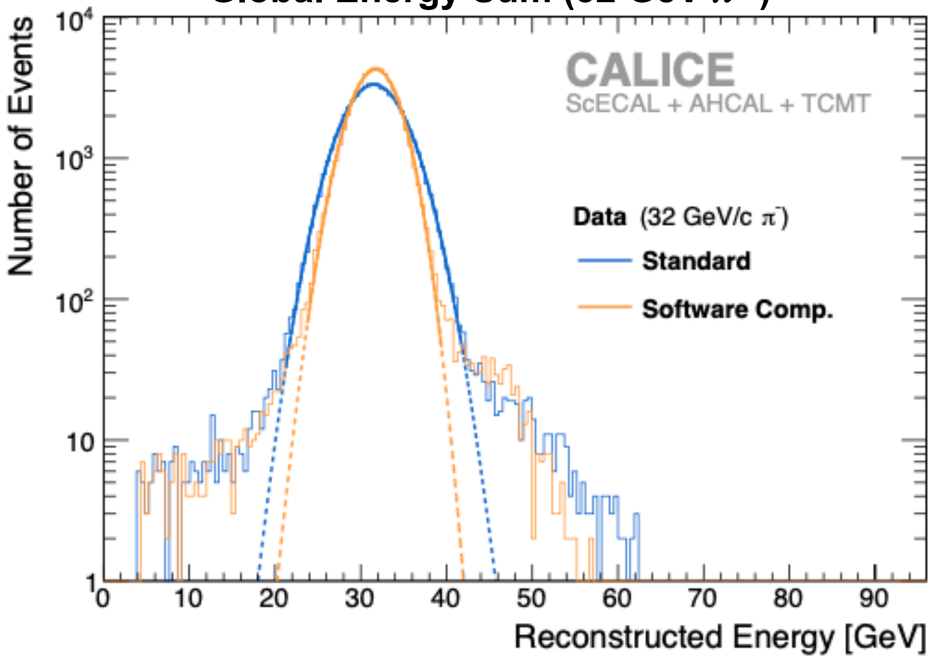
CALICE AHCAL Simulation work in progress

Software Compensation - Analogue Calorimeters

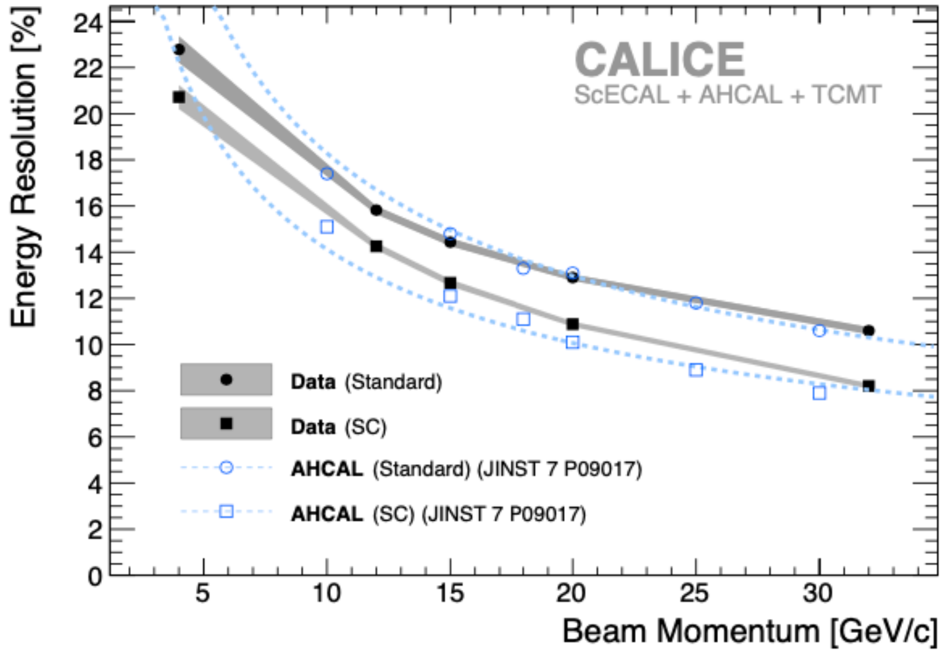
Energy Reconstruction Performance

JINST 13 P12022 (2018)
JINST 7 P09017 (2012)

Global Energy Sum (32 GeV π^-)



Energy Resolution (Standard vs. Software Compensation)



- Within CALICE collaboration software compensation is studied for a variety of detector prototypes
- Here: Combined test beam of ScECAL + AHCAL + TCMT (4-32 GeV π^- @ FNAL)
  - ➡ Energy resolution significantly improved by 10-20% compared to standard reconstruction
    - ➡ With software compensation: **~44.3%** / $\sqrt{E(GeV)}$ ⊕ **~1.8%**