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

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on behalf of the CALICE Collaboration
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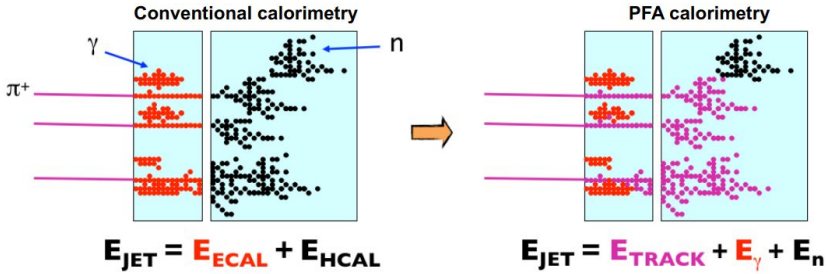
CALICE

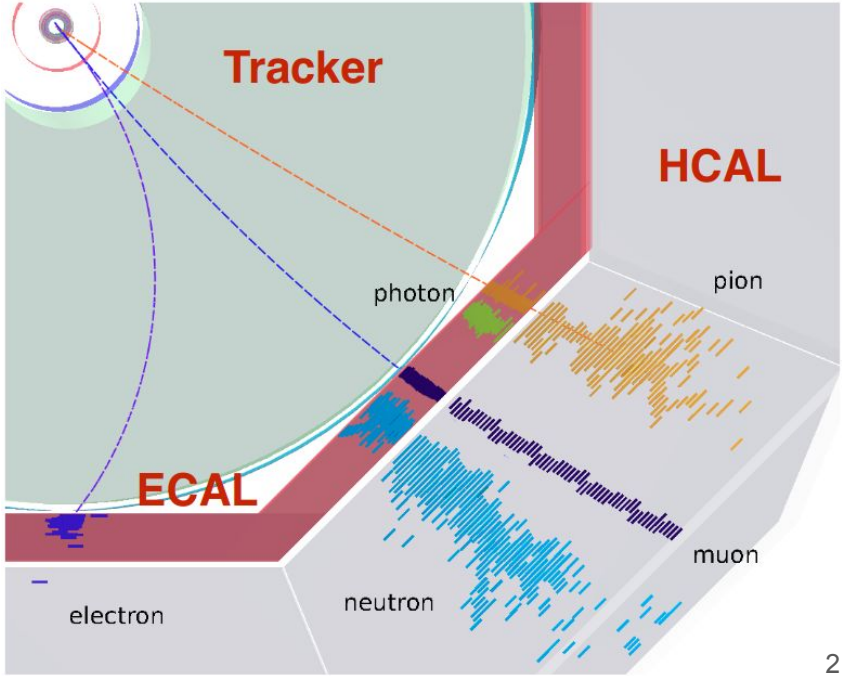
CALICE

What is CALICE?

"The CALICE Collaboration is R&D group of around 280 physicists and engineers from around the world, working together to develop new, high granularity detectors for high energy e^+e^- experiments."

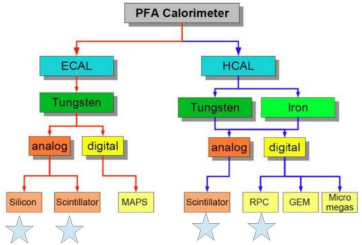
- Future experiments: ILC, CLIC, FCCee, CEPC, LUXE, … → ILD, SiD, … [1 - 4]
- Precision physics and Higgs model independent analysis. [5]
- **REQUIRED:** jet energy resolutions ~3-4% allowing identification of Z^0 and W^{+-} in hadronic decays.
- **APPROACH**: Particle Flow Algorithms [6-7]. New high granularity calorimetry is needed.





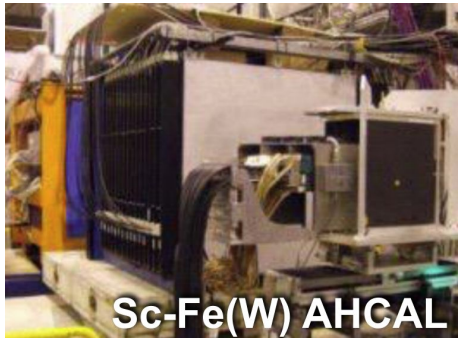
CALICE History

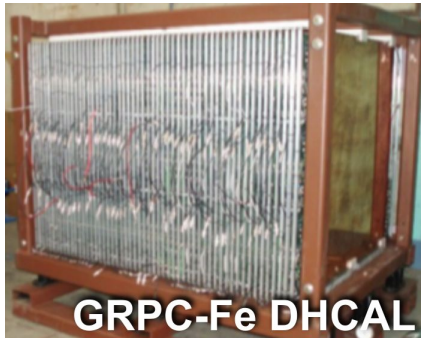
Scintillator, gaseous and semi-conductor technologies



Physics prototypes:

[9]

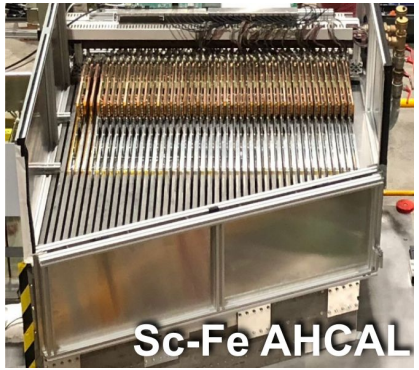




Technological prototypes:

[8]

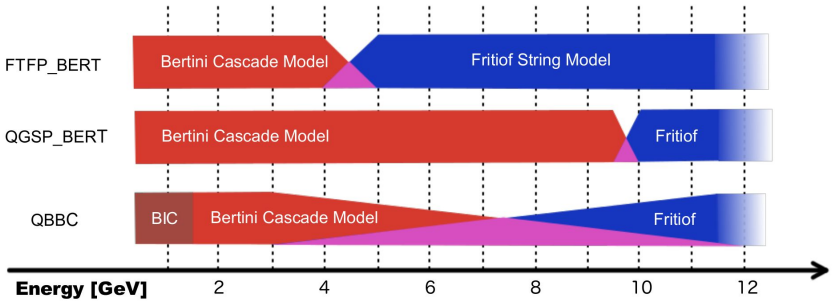
[10]



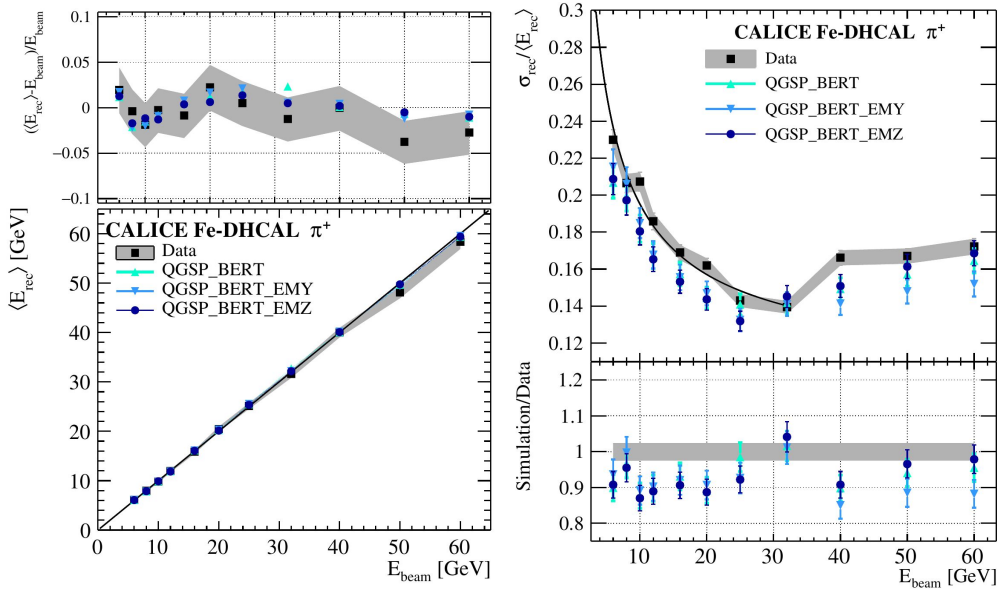
[11]

MC Simulations

- Precise simulation of the interaction of neutral and charged hadrons are needed.
- Mokka [12] framework. Geant4 [13] simulations are a combination of EM and HAD models.
- This models are not perfect and require validation from beam test data.



Nucl.Instrum.Meth.A 939 (2019) 89-105



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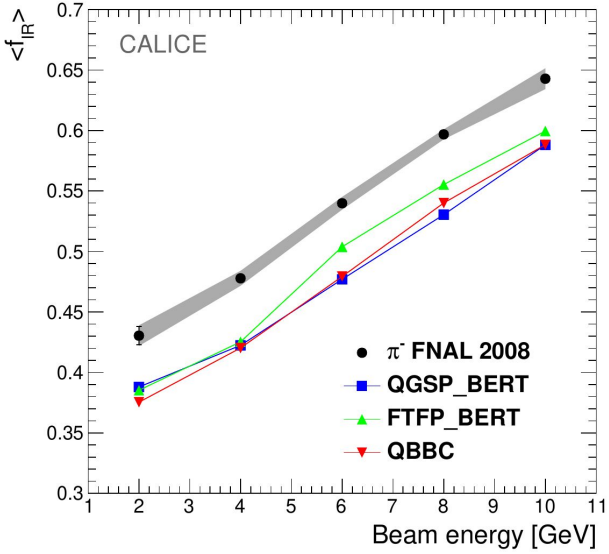
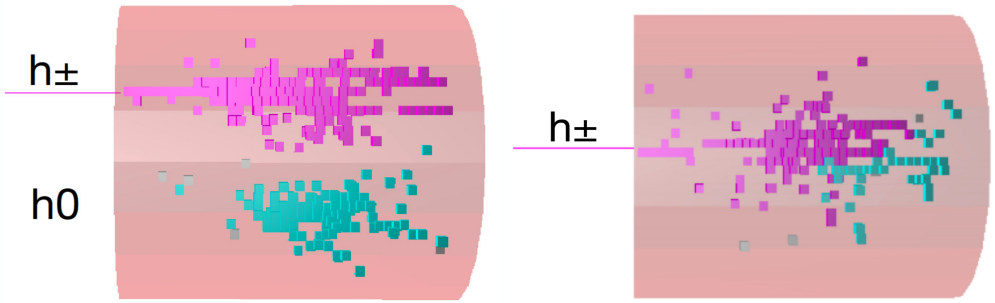


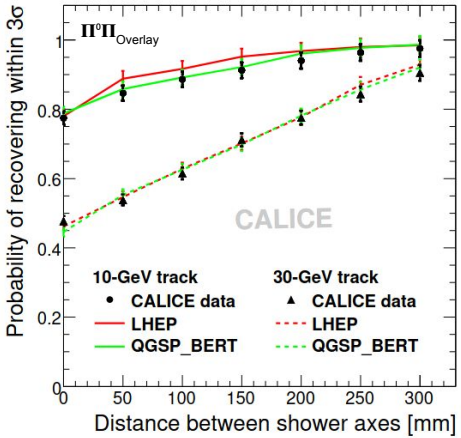
Particle Flow Algorithms - Pandora

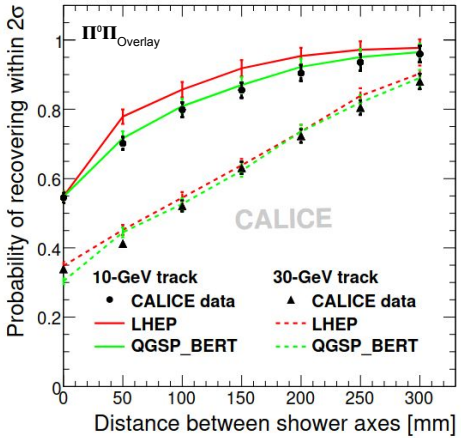
The capability of a PFAs to recover neutral hadron energy in the vicinity of a charged hadron is of crucial importance because mis-assignment of energy would degrade the energy resolution

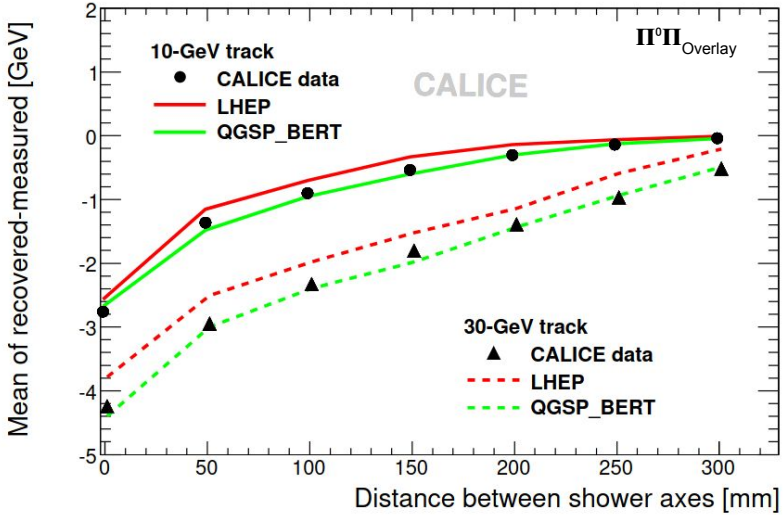
PandoraPFA [6] is the most developed among PFA in the context of ILC being the default reconstruction process.



JINST 6 (2011) P07005



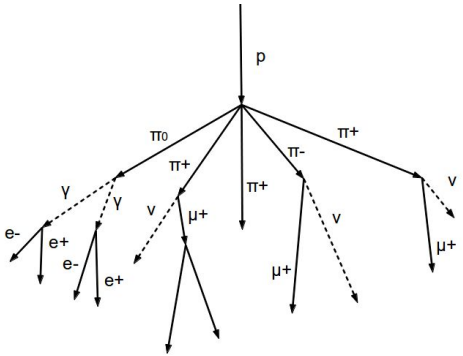


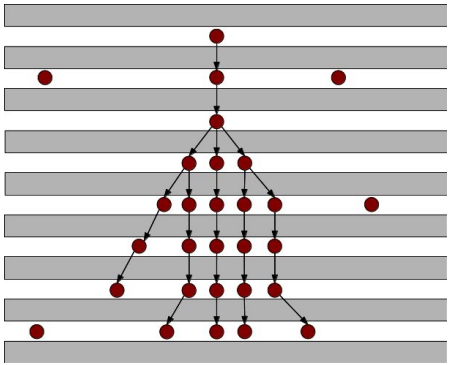


Particle Flow Algorithms - Arbor

This new reconstruction algorithm is based on the tree-like structure of hadronic showers to reconstruct and separate the particles [7].

Tests of single particle reconstruction and multi particle separation have been performed in the context of the SDHCAL prototype.





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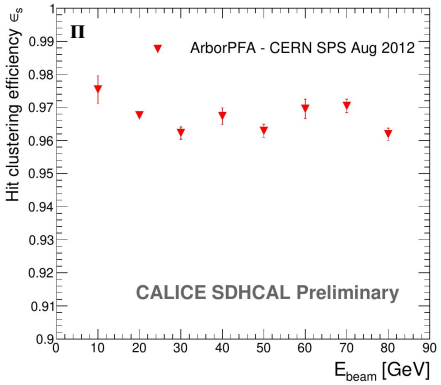
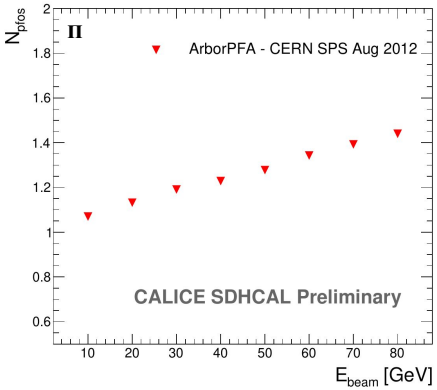
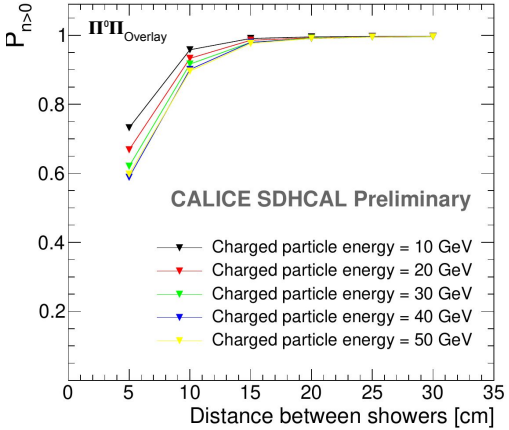
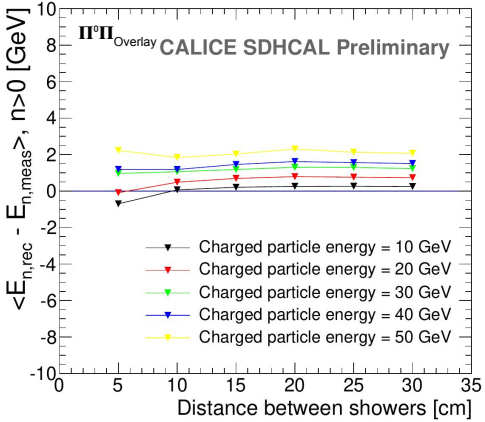








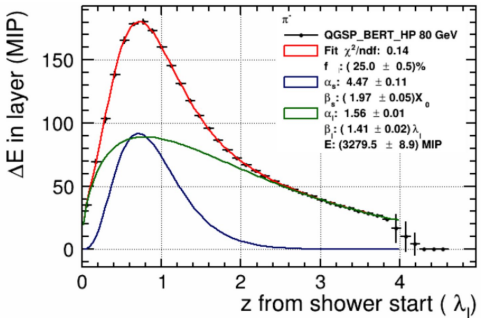
Hadronic shower structure

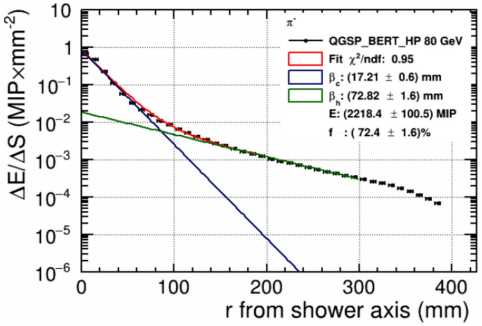
The high granularity of calorimeters allows the study of the different topological properties of the hadronic showers.

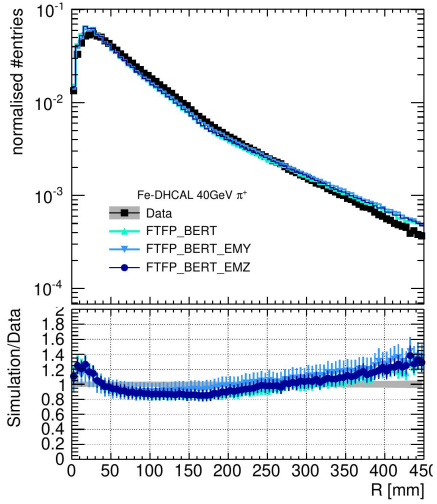
Nucl.Instrum.Meth.A 939 (2019) 89-105

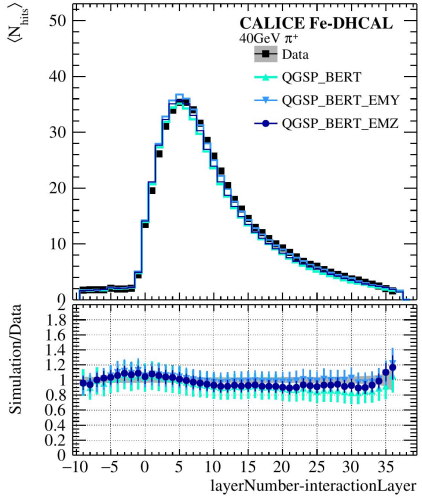
$$\frac{\Delta E}{\Delta S}(r) = \frac{E}{2\pi}\left(f \cdot \frac{e^{\frac{-r}{\beta_c}}}{\beta_c^2} + (1-f)\cdot\frac{e^{\frac{-r}{\beta_h}}}{\beta_h^2}\right)$$

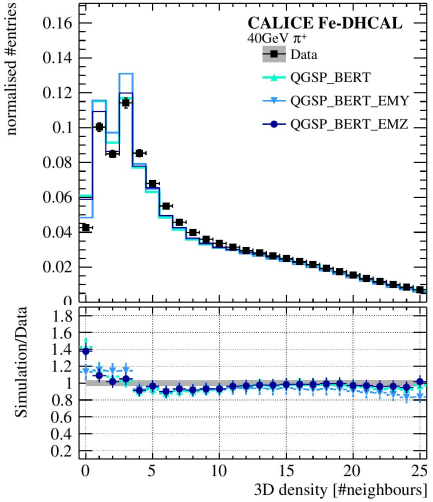
$$\Delta E(Z) = E \cdot \left(\frac{f}{\Gamma(\alpha_s)}\left(\frac{Z[X_0]}{\beta_s}\right)^{\alpha_s - 1}\cdot\frac{e^{\frac{Z[X_0]}{\beta_s}}}{\beta_s} + \frac{1-f}{\Gamma(\alpha_l)}\left(\frac{Z[\lambda_l]}{\beta_l}\right)^{\alpha_l - 1}\cdot\frac{e^{\frac{-Z[\lambda_l]}{\beta_l}}}{\beta_l}\right)$$

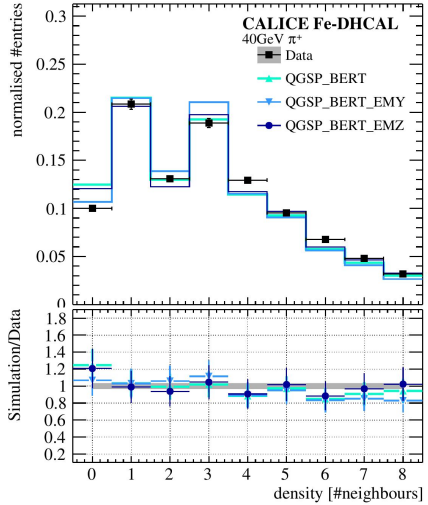








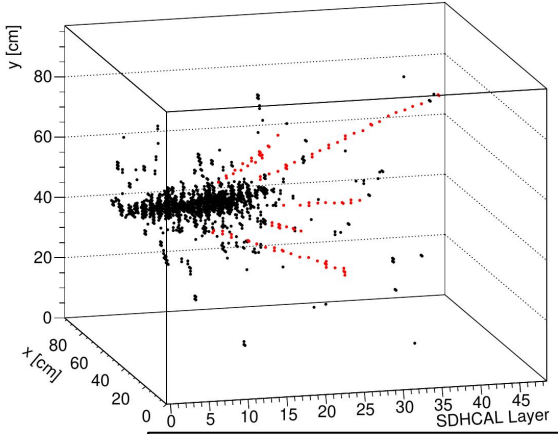




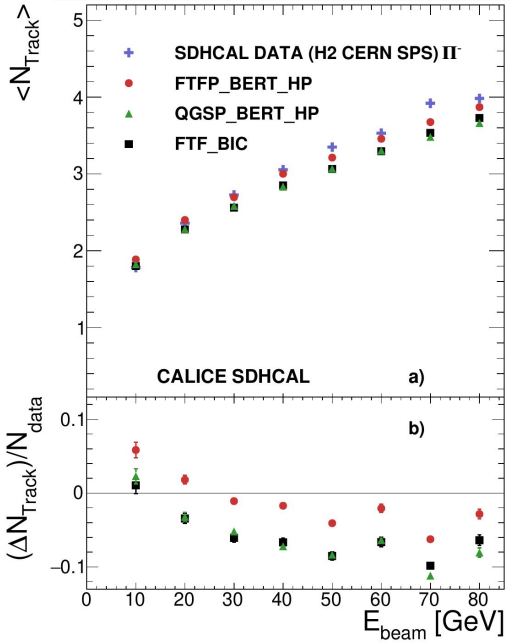
Secondary tracks

Different algorithms for secondary track finding have been successfully developed for the different high granularity prototypes.

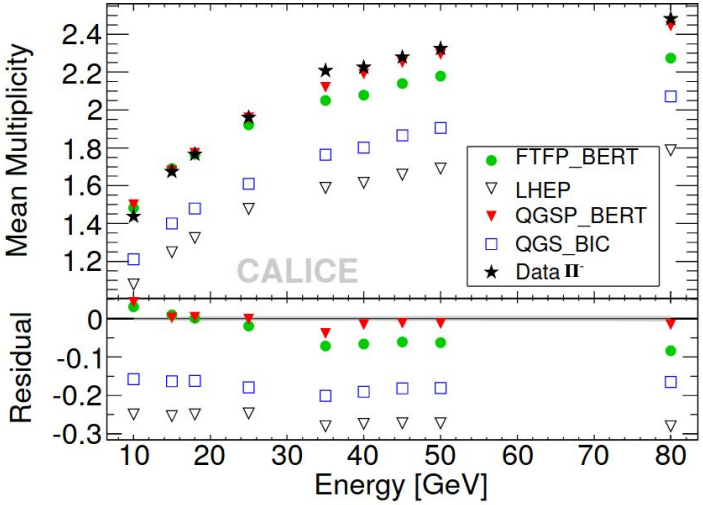
Its information is useful in multi-variate analysis and to improve the energy resolution.



JINST 12 (2017) 05, P05009



JINST 8 (2013) P09001



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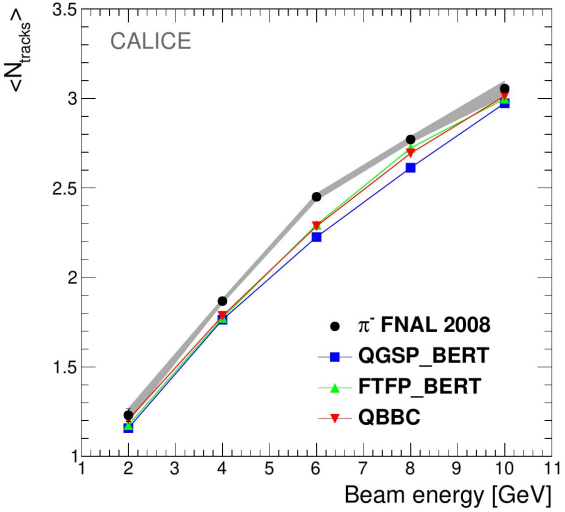
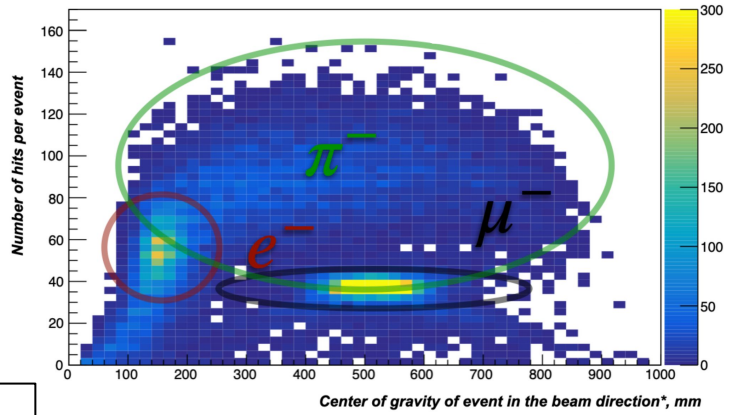


Particle Identification

Multi-Variate Analysis

Efficient identification of particles is a key ingredient to successful particle flow algorithms.

Different variables associated to the topology of the event are exploited to distinguish the particles.

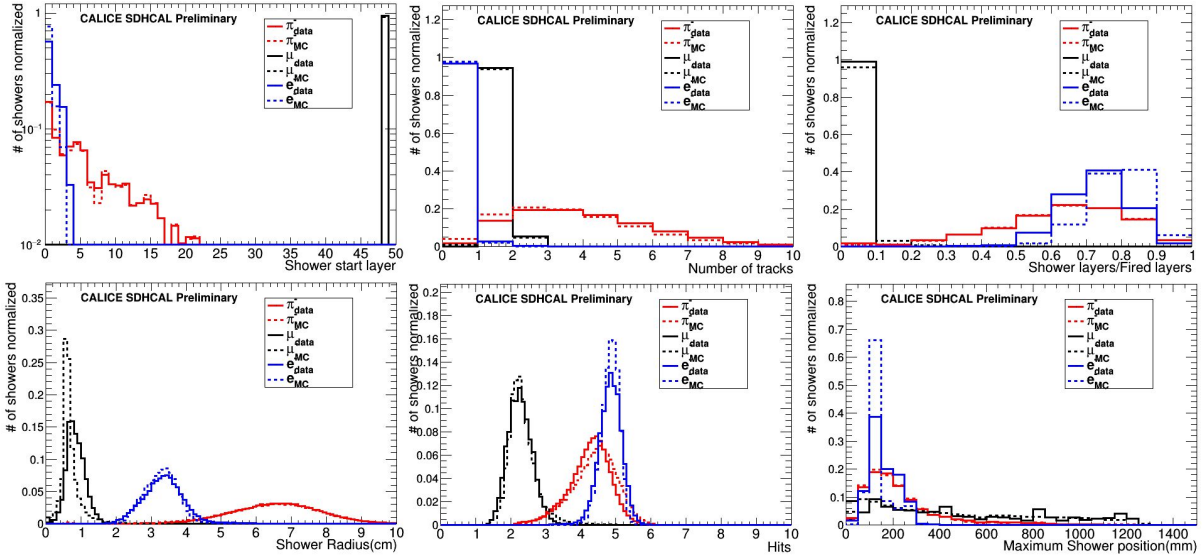


JINST 15 (2020) 10, P10009

SDHCAL BDT:

Training both in data and MC

- First layer of the shower
- Number of tracks segments in the event
- Ratio of shower layers vs total layers
- Shower density
- Shower radius
- Maximum shower position



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JINST 15 (2020) 10, P10009

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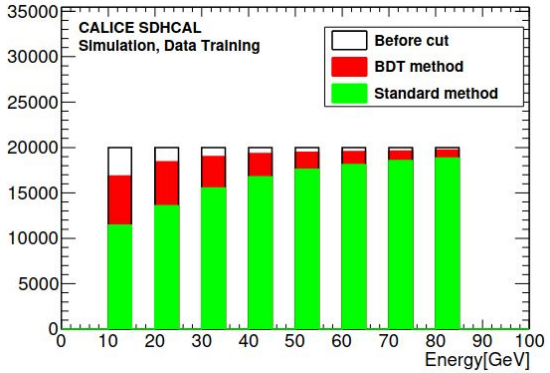
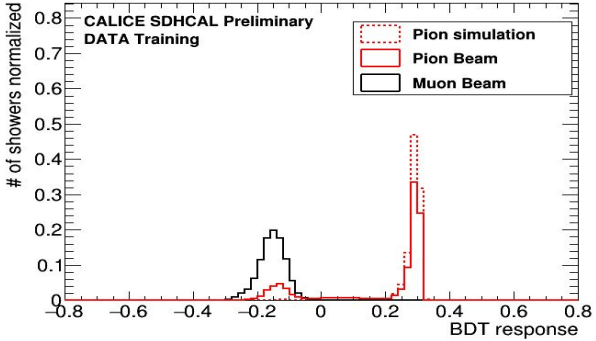
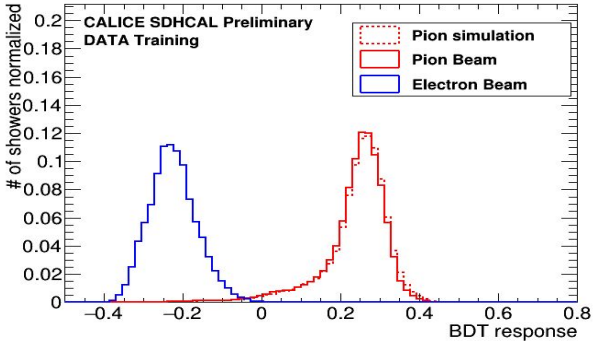
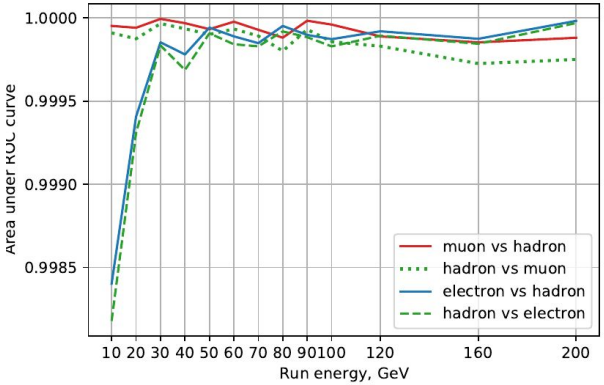


SDHCAL BDT:

Stable performance on a wide range of energies →







← **AHCAL MVA**:

Currently ongoing analysis

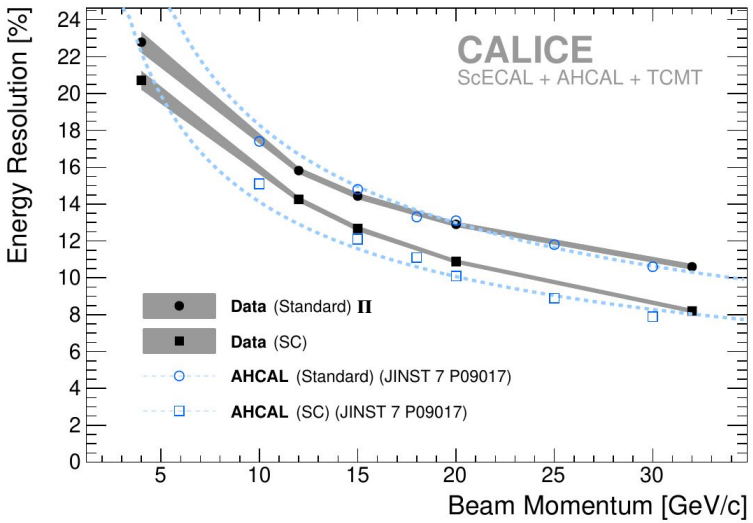
Software Compensation

Non-compensating analogue calorimeters

Aims to correct for the calorimeter different response to electromagnetic and hadronic interactions e/h ≠1 in analog non compensating calorimeters.

- Significant energy resolution improvement 10 - 20% in Fe absorber

JINST 13 (2018) 12, P12022



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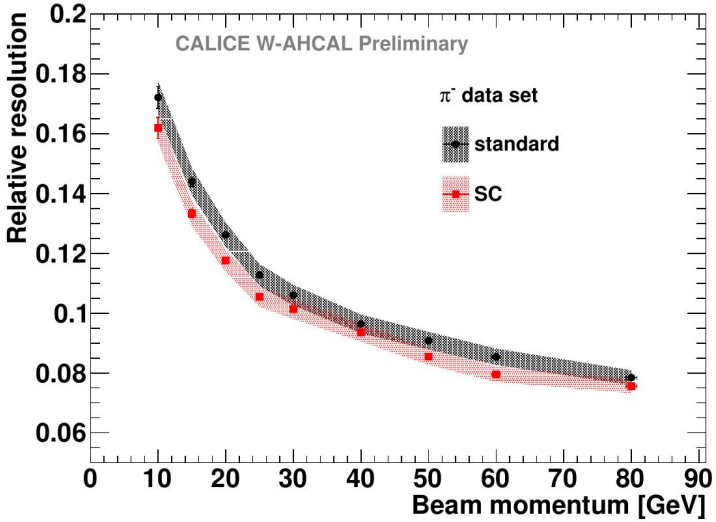
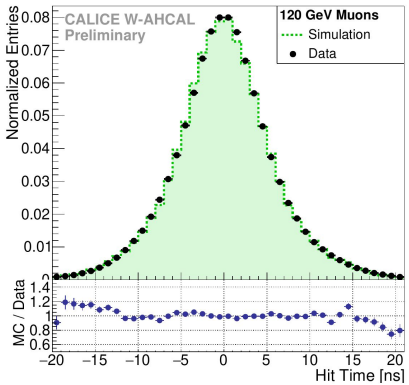
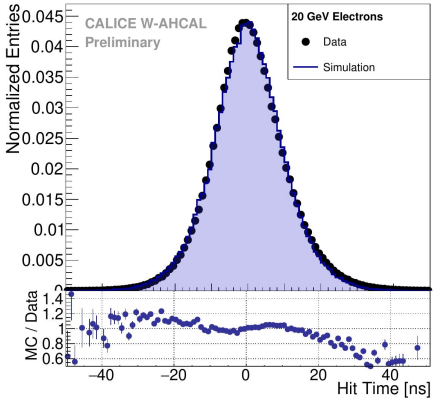


Timing

Study of the time structure of particles

- **AHCAL** technological prototype hit time measurement capability. *Fe* and *W* absorbers.
- Time scale: ~1 ns
- MIP event time resolution: ~6ns
- Wider e^- resolution due to high occupancy in the electronics.
- Slow neutrons produce tails in the hadronic time distribution.





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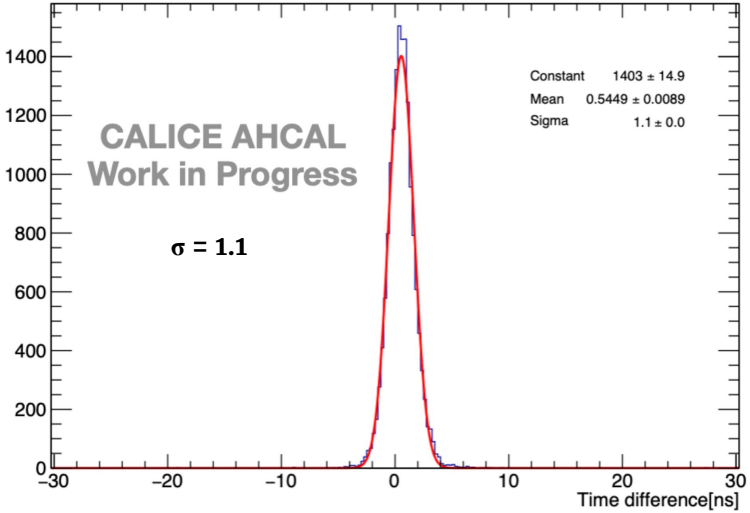
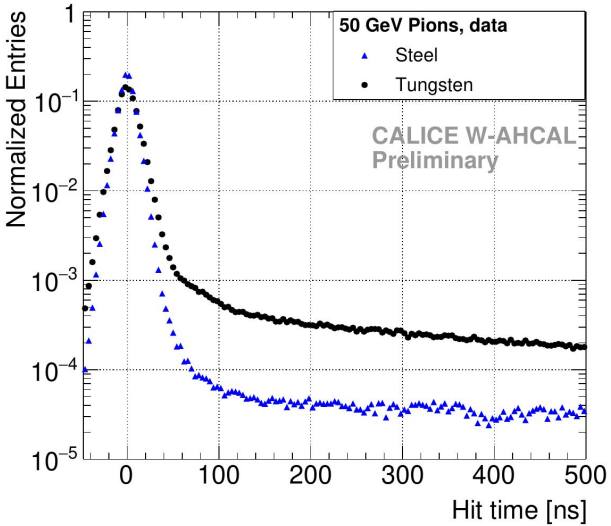
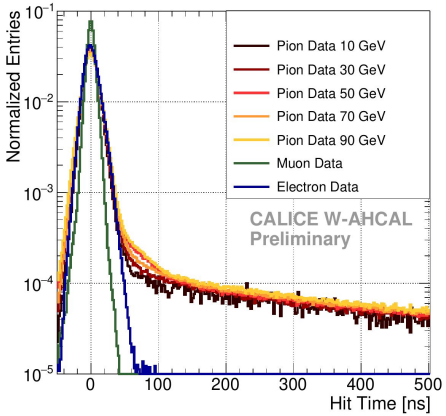






Summary

- 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 reconstruction using software compensation
- Timing measurements show promising results
- Many other analyses with the CALICE technological prototypes are ongoing
- More about the technological prototypes in the poster Implementation of large imaging calorimeters by Robert Bosley.

Backup

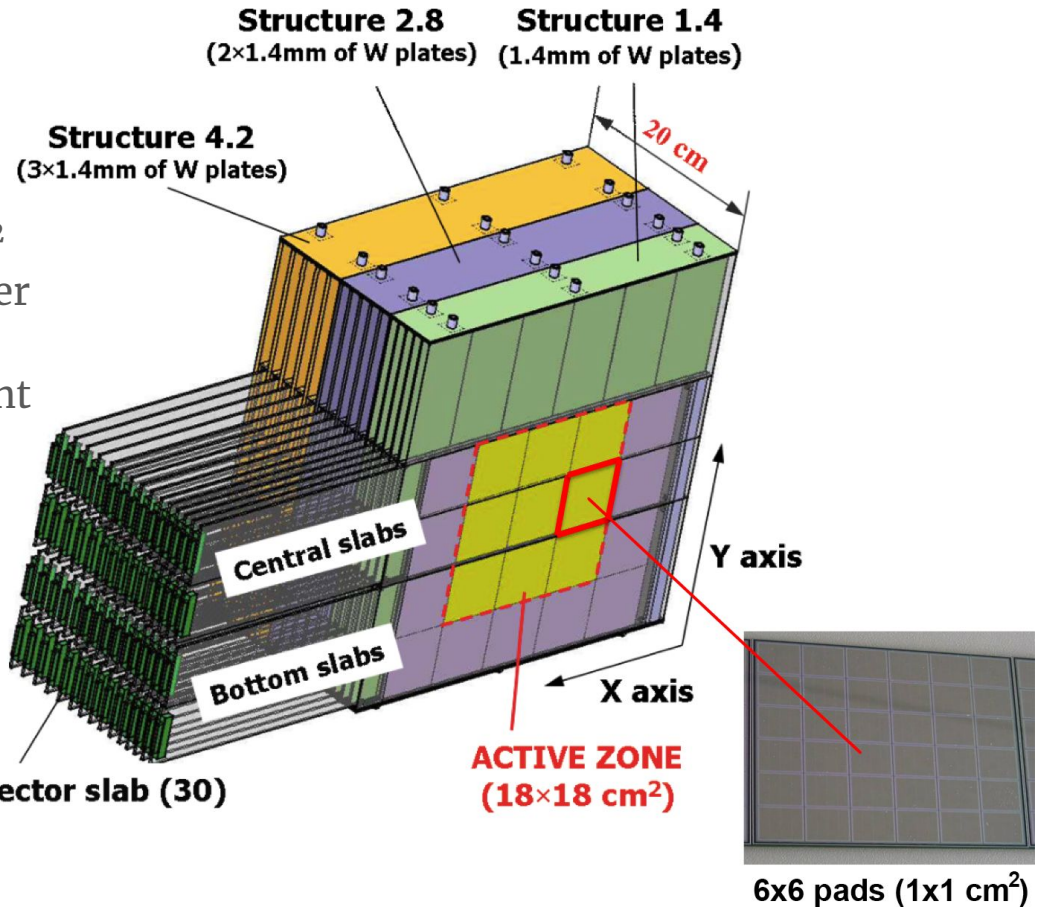
References

[1] ILC-REPORT-2013-040
[2] CERN-2012-003
[3] Eur. Phys. J. Spec. Top. 228, 261–623 (2019)
[4] DESY 20-034
[5] ILC-REPORT-2013-040
[6] AIDA-CONF-2014-002
[7] CU-HEP-09/11
[8] Nucl.Instrum.Meth.A 950 (2020) 162969
[9] Nucl.Instrum.Meth.A 887 (2018) 150-168
[10] J.Phys.Conf.Ser. 1162 (2019) 1, 012012
[11] JINST 10 (2015) 10, P10039
[12] LC-TOOL-2003-010
[13] Nucl.Instrum.Meth.A 835 (2016) 186-225

Si-W ECAL

Physics Prototype

- Silicon as the active material and tungsten as the absorber.
- Transversal segmentation of 1x1 cm^2 pads in a matrix of 6x6 pads per wafer and 3x3 wafers per layer.
- 30 layers in three modules of different tungsten depth.
- Total thicknes ~1 λ_I

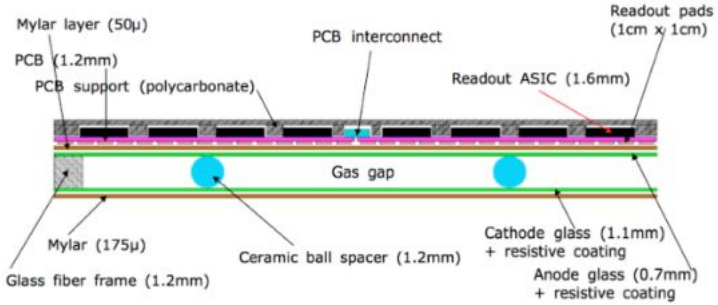


SDHCAL

Technological Prototype

SDHCal: 48 active layers $1x1m^2$ GRPC with $1x1cm^2$ pads. The absorber plates are 15 mm thick stainless steel.

ASIC HARDROC(64 channel)
three-threshold (Semi-digital)
110fC,5pC,15pC



$(0.12\lambda_I, 1.14X_0)$

Stainless steel Absorber(15mm)

Stainless steel wall(2.5mm)

GRPC(6mm$\approx 0\ \lambda_I, X_0$)

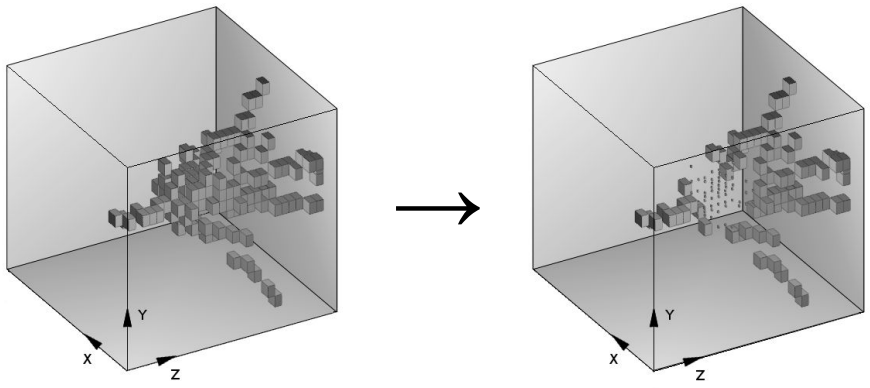
Stainless steel wall(2.5mm)

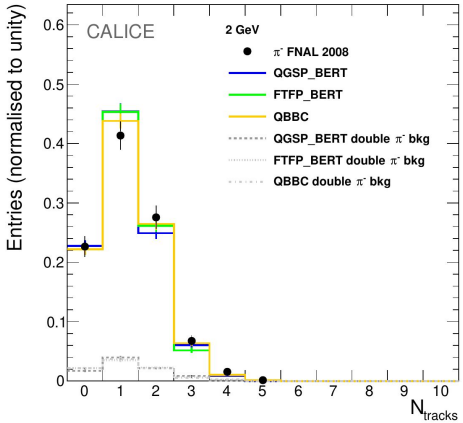
Si-W ECAL

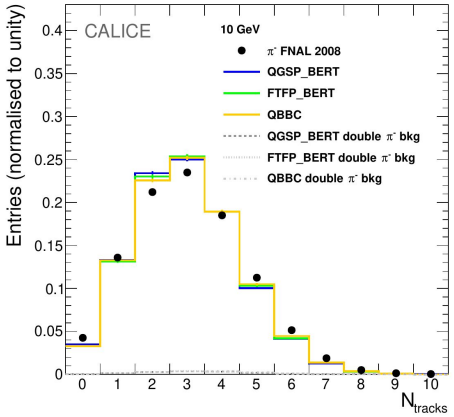
Track finding

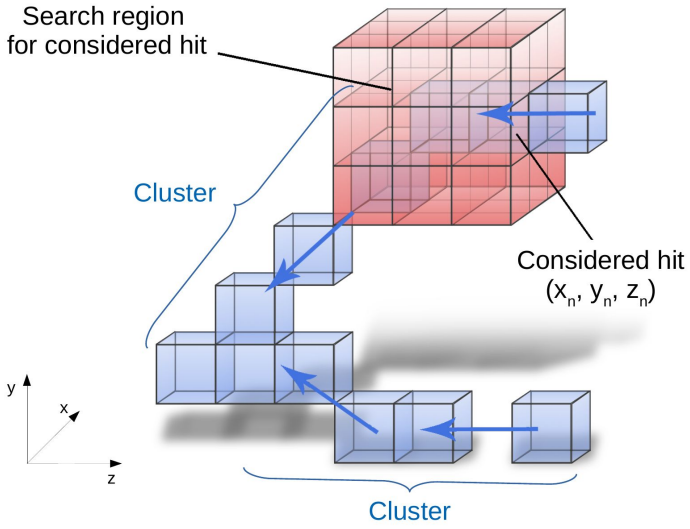
Reconstructs forward-scattered tracks from the interaction between the hadron and the absorber material in the absence of a magnetic field.

- Identification and removal of the interaction region.
- Clusterization of energy deposits.
- Formation of tracks.









Si-W ECAL

Hadronic shower structure

The high granularity allows for observables characterising the interaction region and secondary particles.

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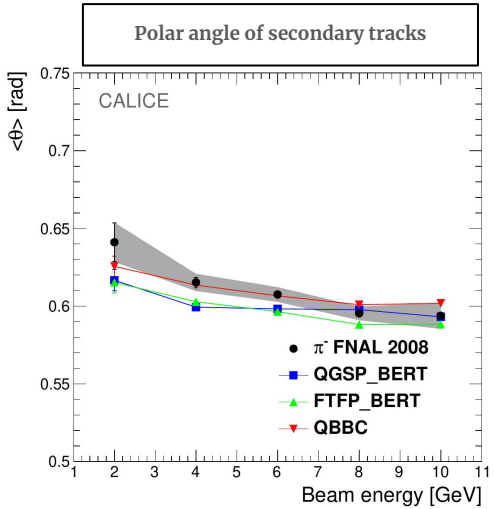

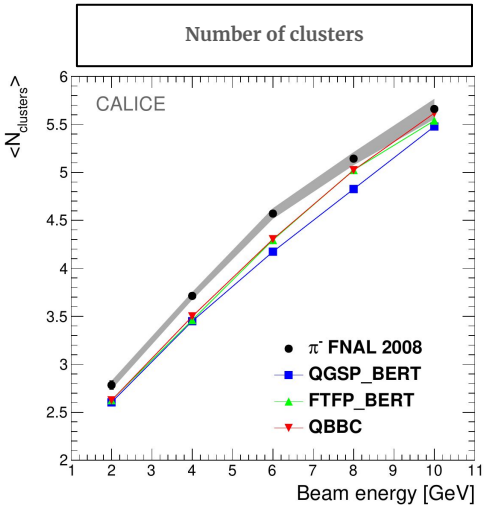

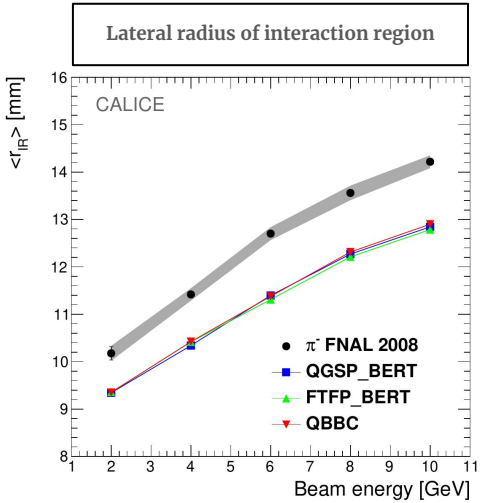

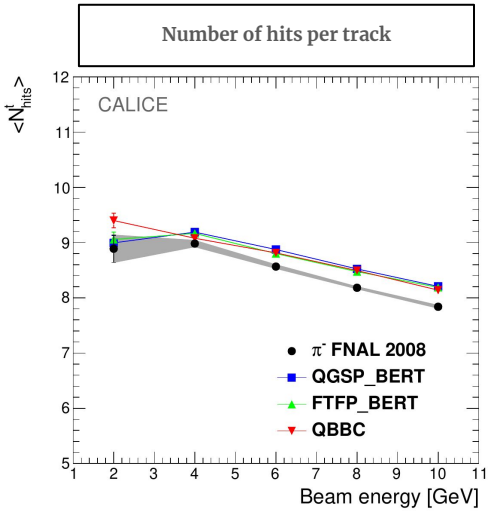

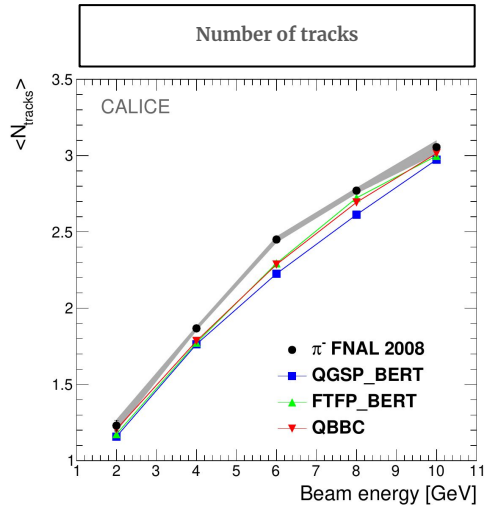

DHCAL

MC Simulation EM physics list

Digitization parameters are determined from data. The tuning is done by matching the N_{hits}/layer for different physics list.

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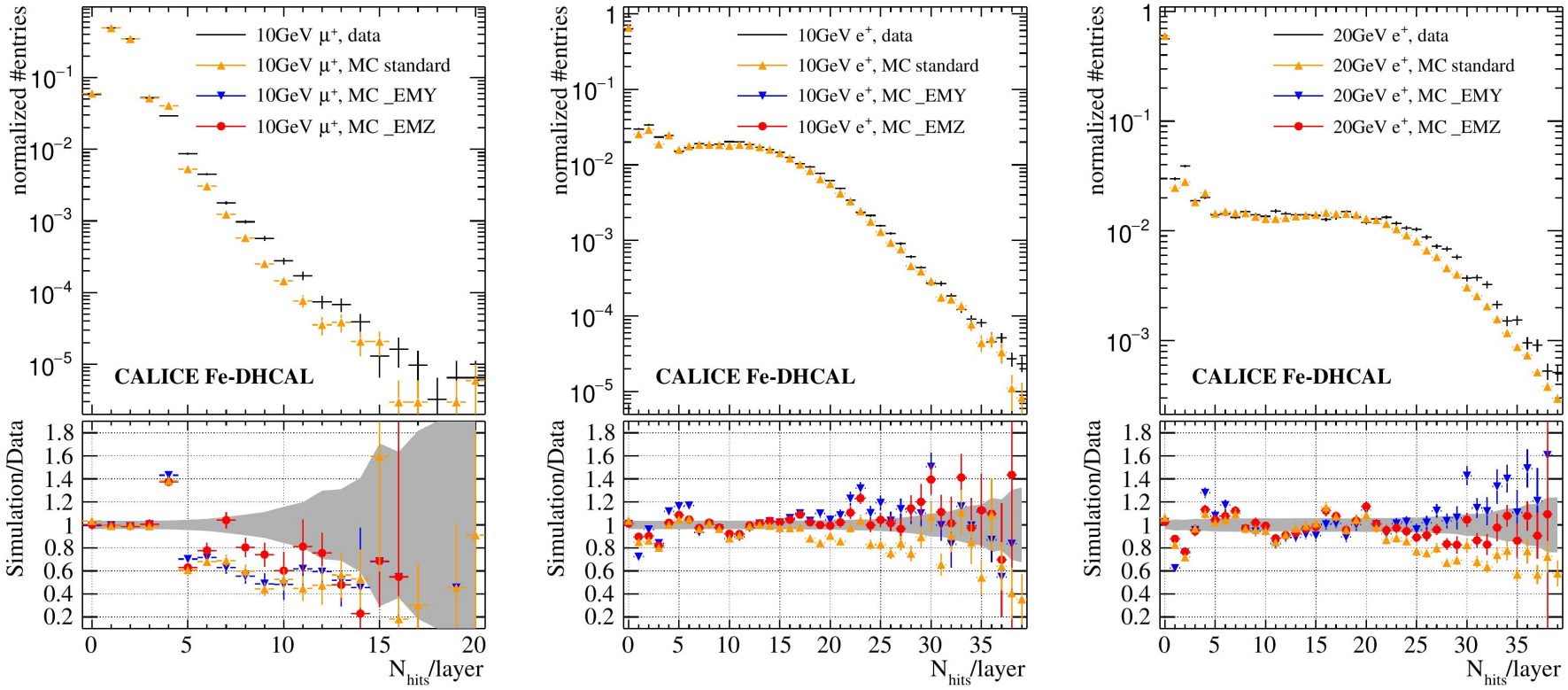

DHCAL

MC Simulation HAD physics list

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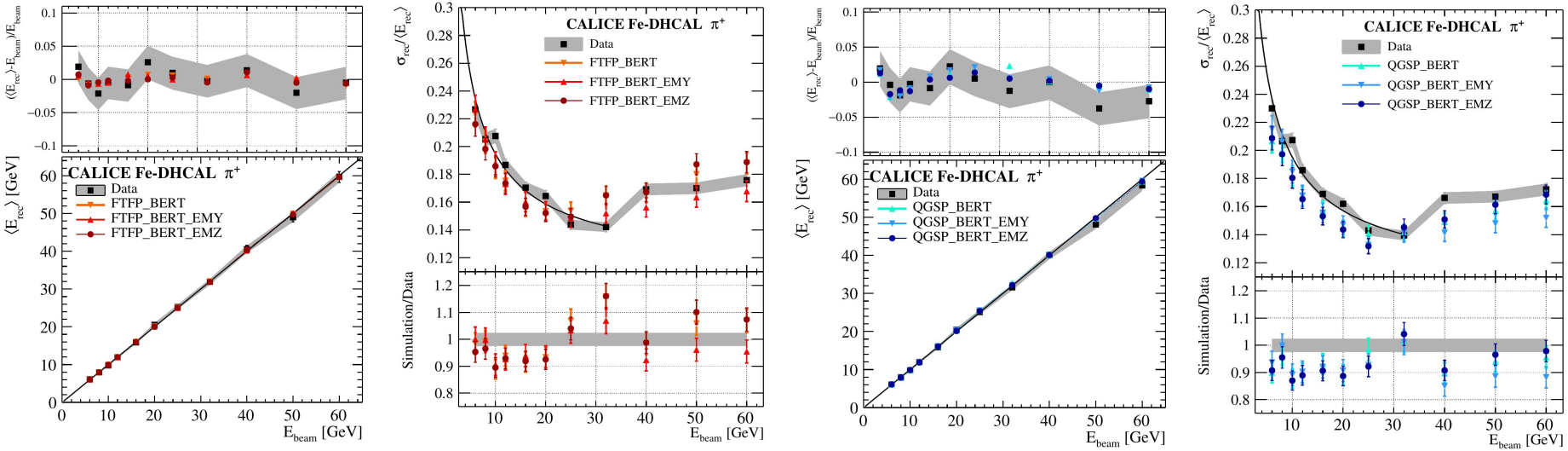
There is a strong dependence on EM and HAD physics lists with linearity deviations less than 2% and resolution less than 15%



DHCAL

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Hadronic shower shapes