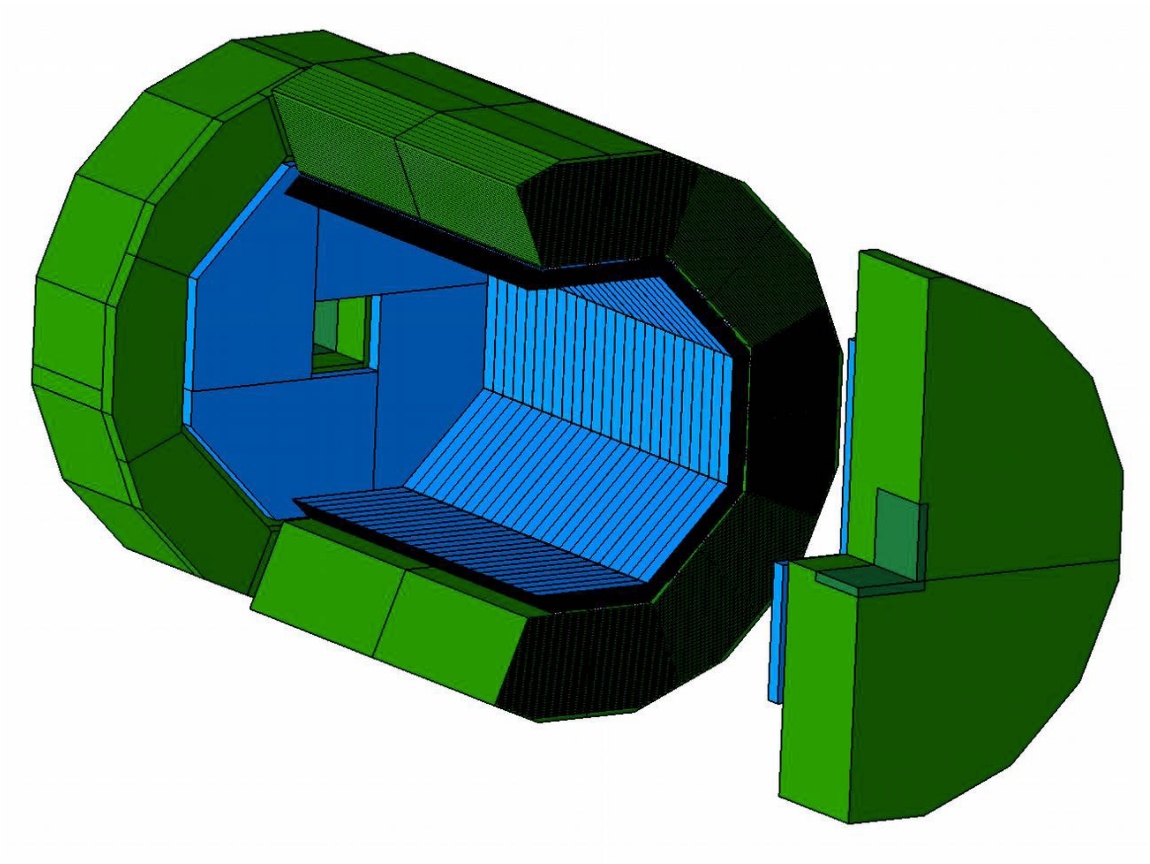
LC calorimetry: recent developments in simulation, reconstruction & optimisation



Katja Krüger
ILC project meeting,
11 November 2016

Introduction

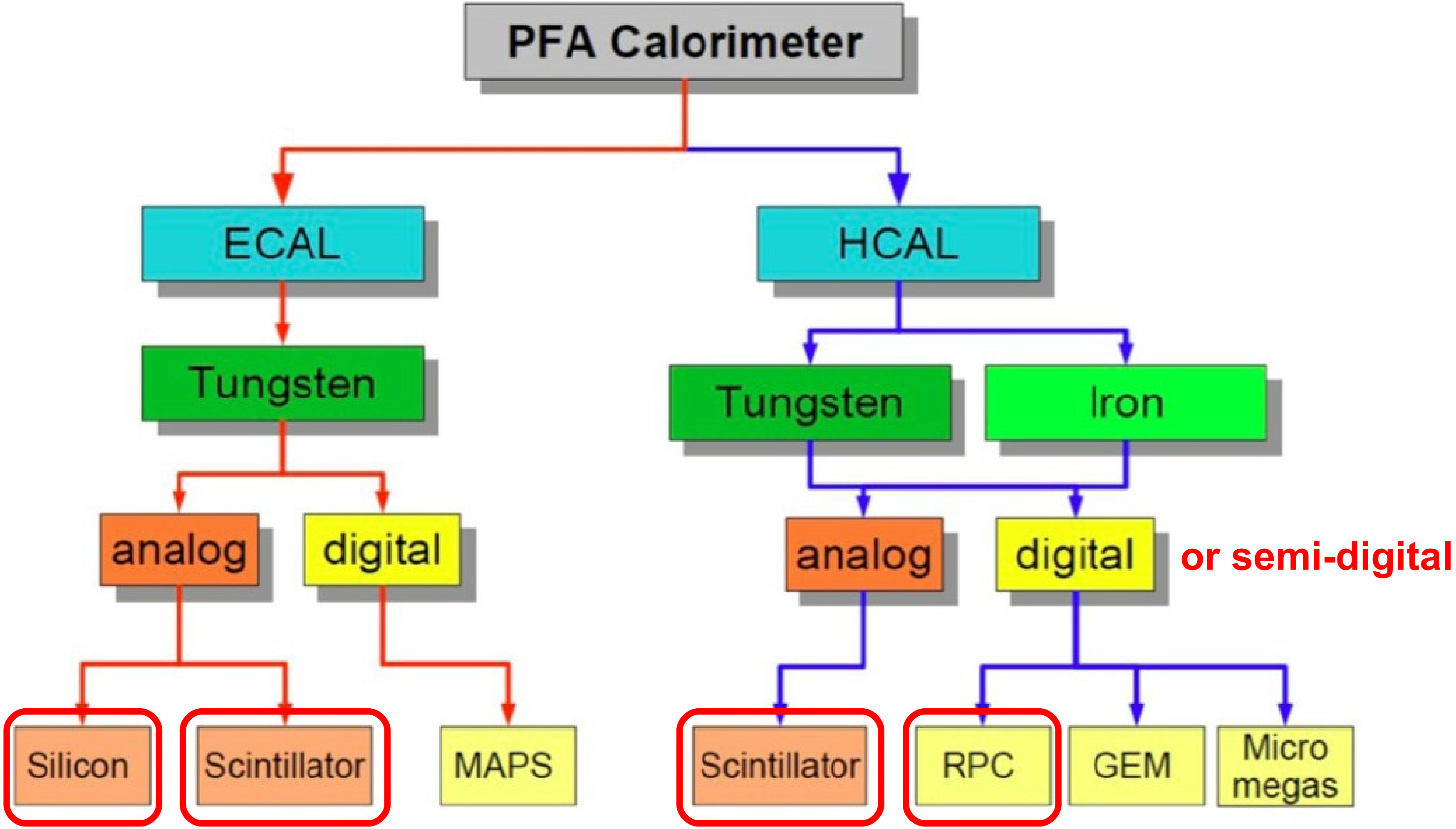
- high granularity calorimetry is a key component for all linear collider detectors to reach required jet energy resolution by applying Particle Flow Algorithms

- unprecedented granularity leads to new challenges:
  - for building such detectors
  - **for modeling of the detector response**
  - **for modeling of hadronic showers**

- unprecedented granularity leads to new opportunities
  - **optimum use of the detailed shower information in the reconstruction (software compensation)**
  - **interplay of reconstruction algorithms with detector optimisation**

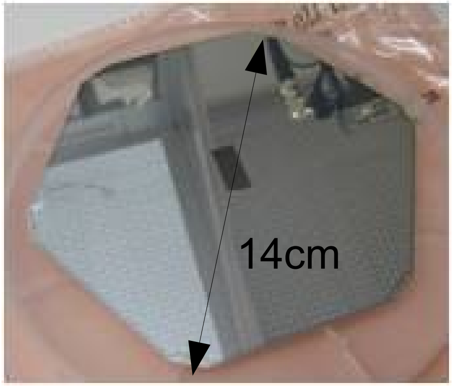
Calorimeter Prototypes

Calorimeter Technologies for Linear Collider detectors

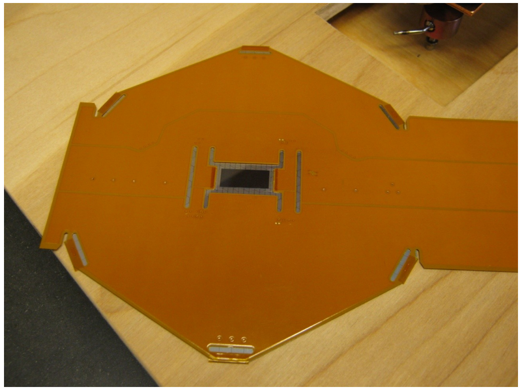


Electromagnetic Calorimeter

Silicon

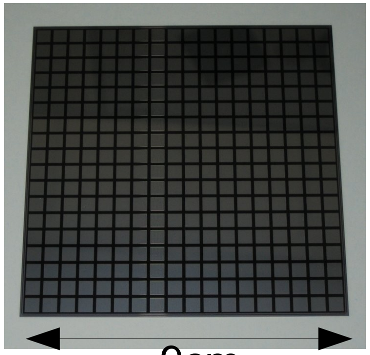


1024 pixel



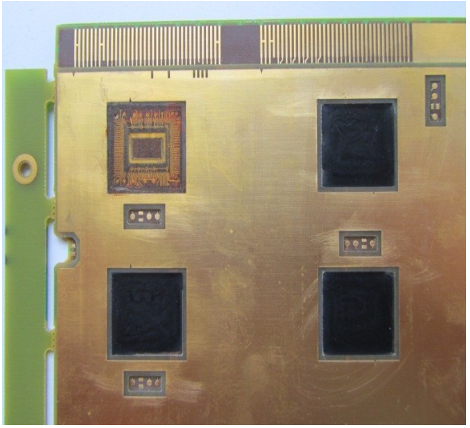
SiD

Silicon



9cm

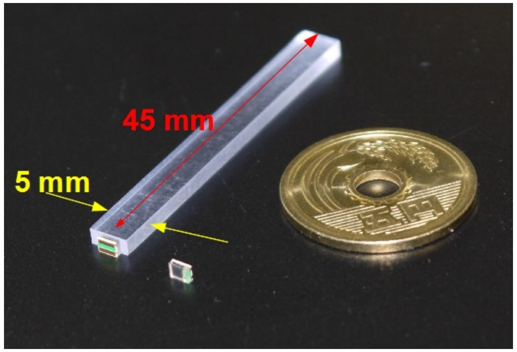
256 pixel



ILD option

SiECAL

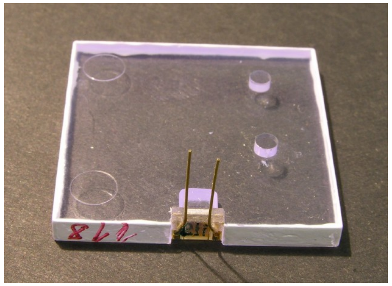
Scintillator

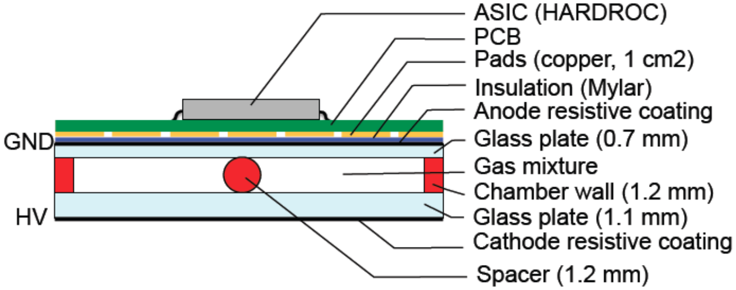


ILD option

SciECAL

Hadronic Calorimeter





- Scintillator tiles read out by SiPMs
- 3*3 cm^2 tiles
- readout: 12 bit (analog)
- **ILD option**
  SiD

AHCAL

- Resistive Plate Chamber: local gas amplification between 2 glass plates with high voltage
- 1*1 cm^2 readout pads
- readout: 1 bit (digital)
- **SiD alternative**

DHCAL

- readout: 2 bit (semi-digital)
- **ILD option**

SDHCAL

Modeling of the detector response

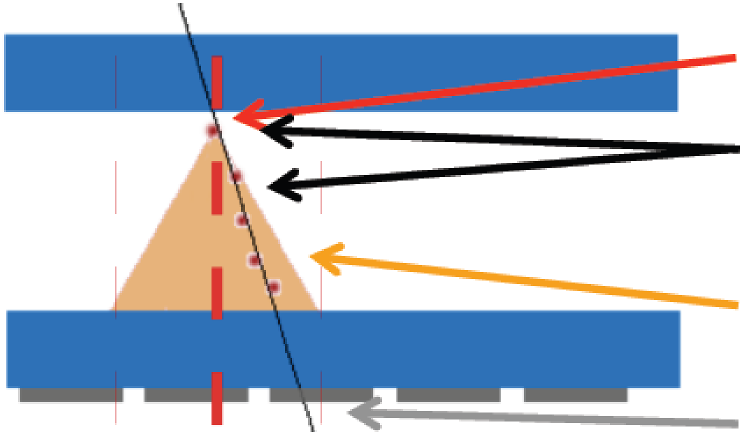
Modelling of the detector response

- use particles with well-known detector response to tune the simulation
  - muons for the response to single particles
  - electrons for the response to dense showers
- check different aspects of the simulation
  - materials described correctly?
  - digitisation effects:
    - SiPM saturation due to limited number of pixels
    - charge spreading in avalanches in gas
    - time cuts (integration time of electronics)
- scintillator well known as sensitive material in calorimeters
- RPCs are not sensitive to average dE/dx, but to the number of points of ionisation → tests different aspect of simulation than scintillator

RPC digitisation

many aspects of the RPCs are modelled in the digitisation step

- measured charge Q_{tot} given by initial charge q_0 and measured RPCs induced charge spectrum q_{ind} (depends on HV, gas pressure, …)
- overlapping avalanches will screen each other
- avalanche will spread the charge over several readout pads
- readout pads have a threshold T



$$Q_{tot} = q_0 \cdot q_{ind}$$

$$d_{dist} < d_{cut} \rightarrow Q_{tot} \cdot s$$

$$f(r) = (R-1) \cdot \exp\left(-\frac{r^2}{2\sigma_1}\right) + R \cdot \exp\left(-\frac{r^2}{2\sigma_2}\right)$$

$$T$$

- very sensitive to number and position of the energy deposition in the simulation
- DHCAL and SDHCAL were operated in different conditions, so individual tuning is necessary

DHCAL comparison to simulation

- simulation tuned with muons and electrons
- DHCAL configuration without absorber: detailed shower profiles

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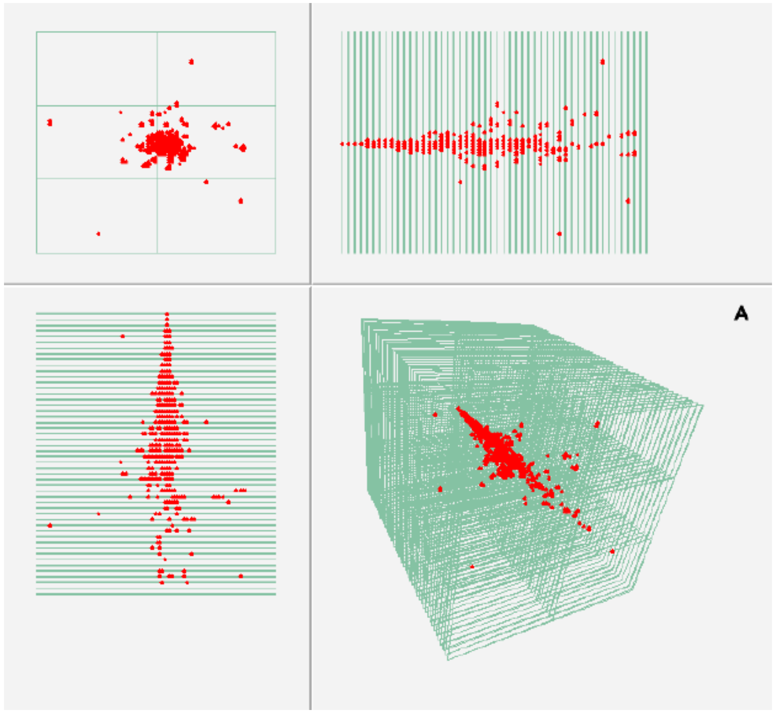
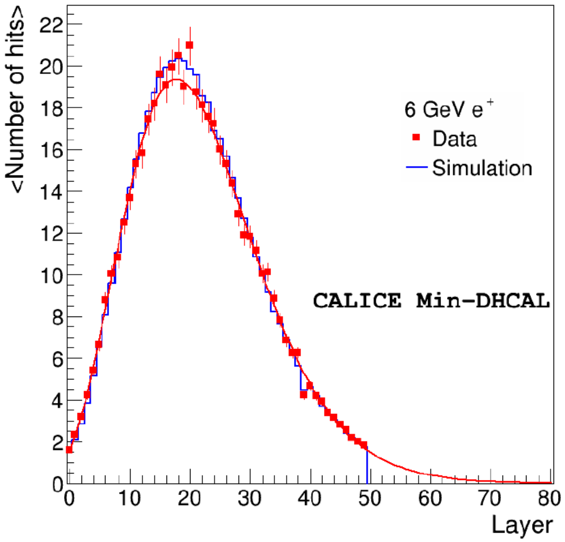
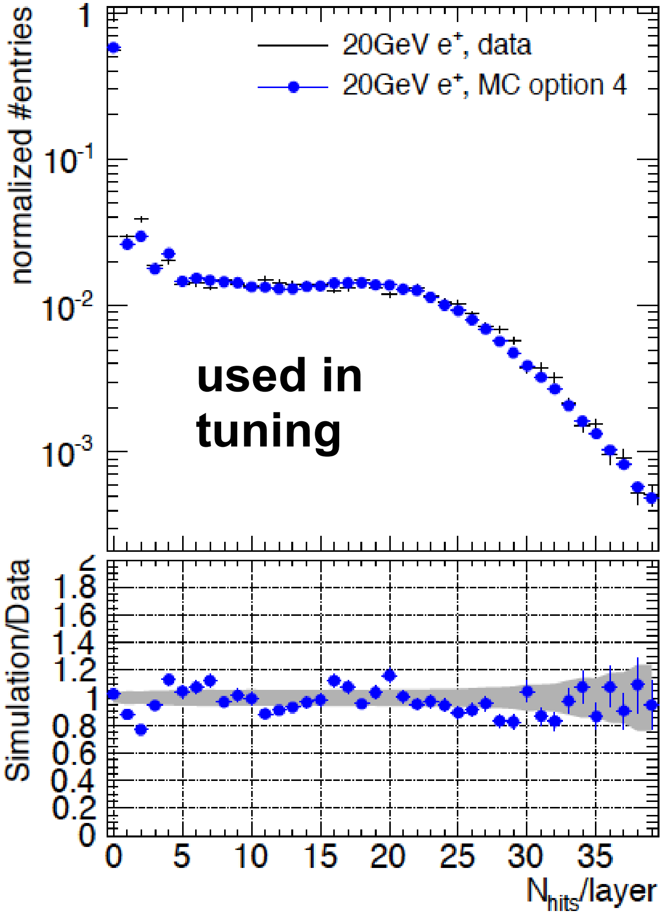




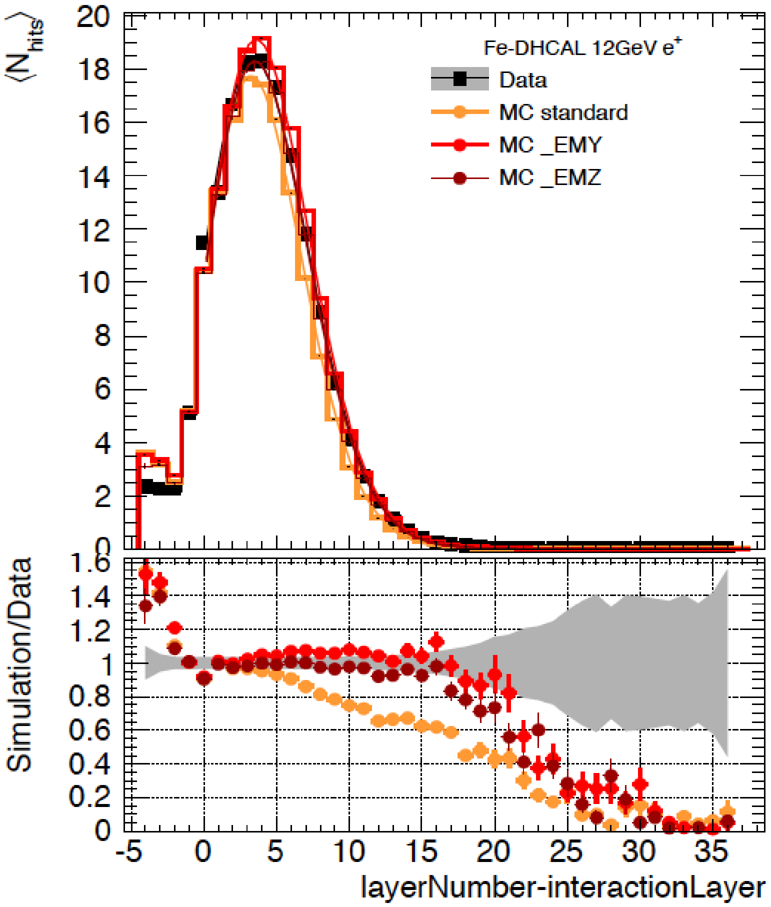
DHCAL comparison to simulation

C. Neubüser
PhD thesis

- simulation tuned with muons and electrons
- very sensitive to step width in simulation



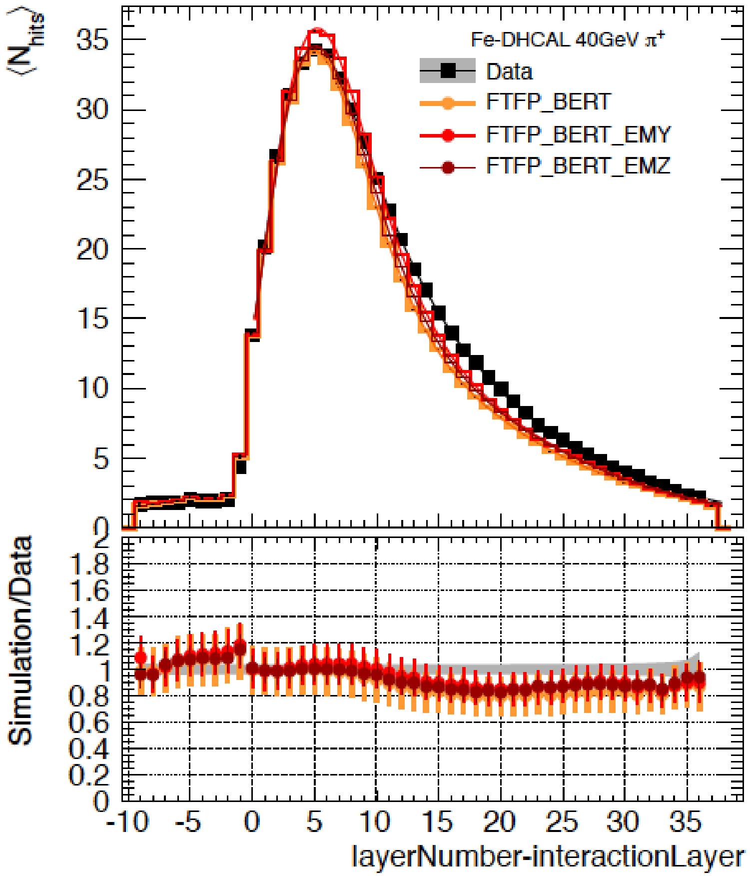
used in tuning

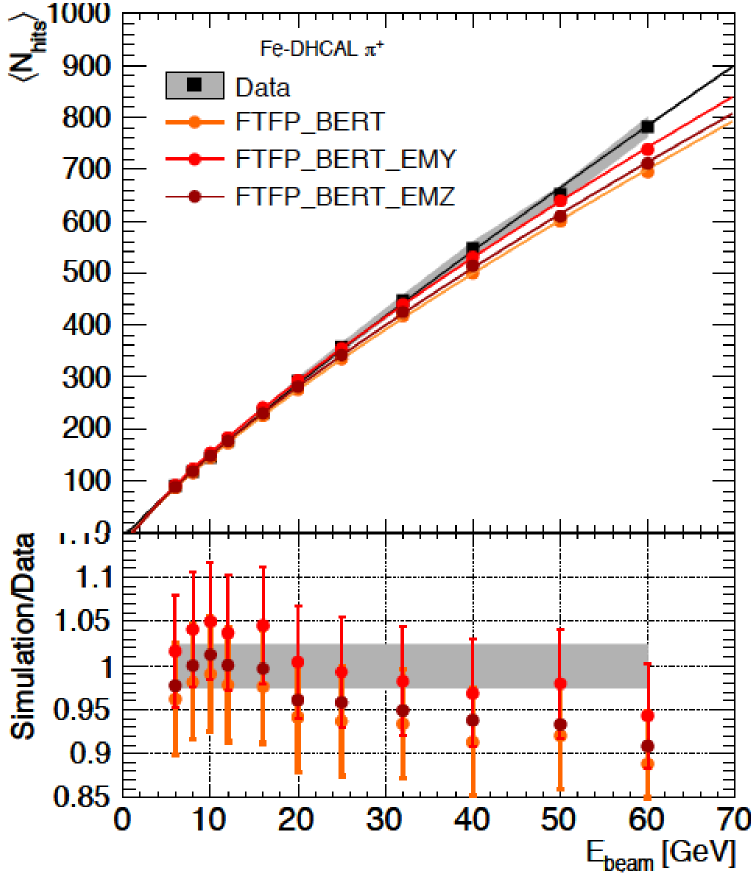


DHCAL comparison to simulation

C. Neubüser
PhD thesis

- simulation tuned with muons and electrons
- pion shower shapes rather well described, response at large energies slightly underestimated





SDHCAL comparison to simulation

- simulation tuned with muons and electrons
- leads to reasonable description of pion showers, response at large energies slightly underestimated

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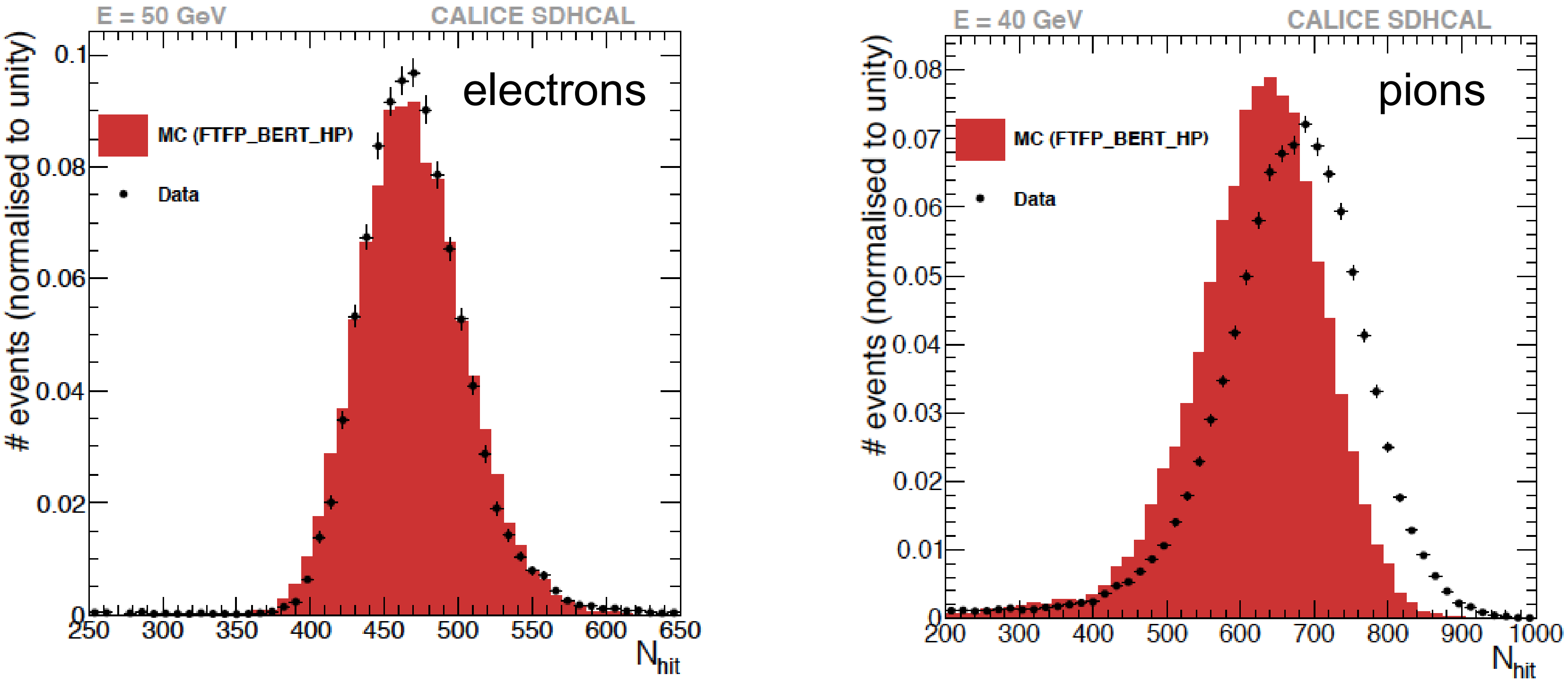
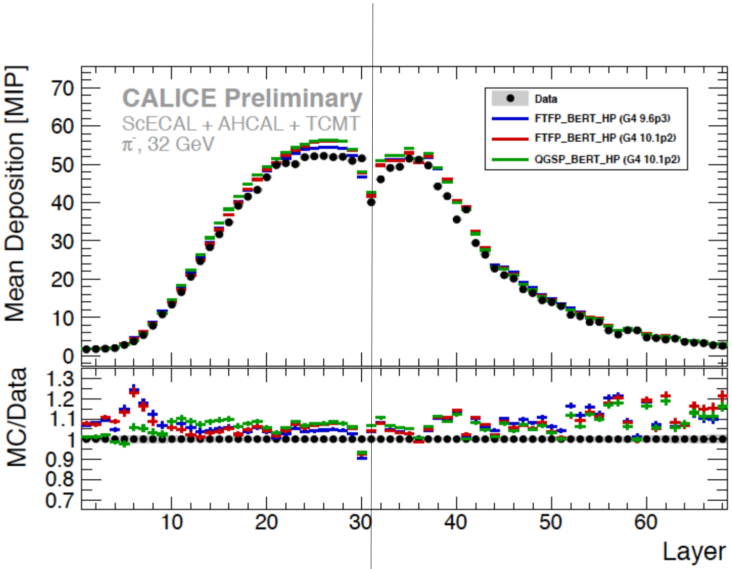


Combined scintillator calorimeter system

- in a real calorimeter system, hadrons are not measured purely in HCAL, but in ECAL + HCAL (+tailcatcher)
- ECAL and HCAL typically have different absorber, sampling ratio, active material
- combined system of scintillator-tungsten ECAL + scintillator-steel AHCAL well described in simulation

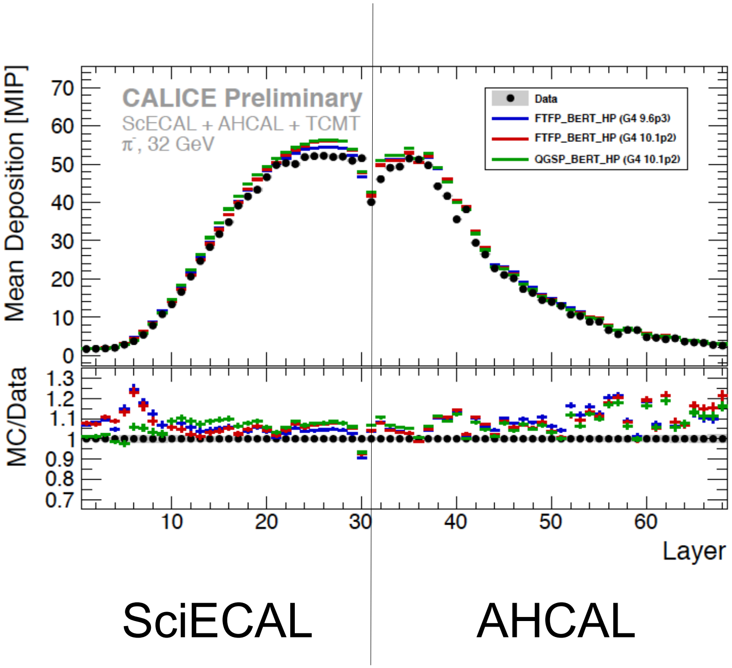


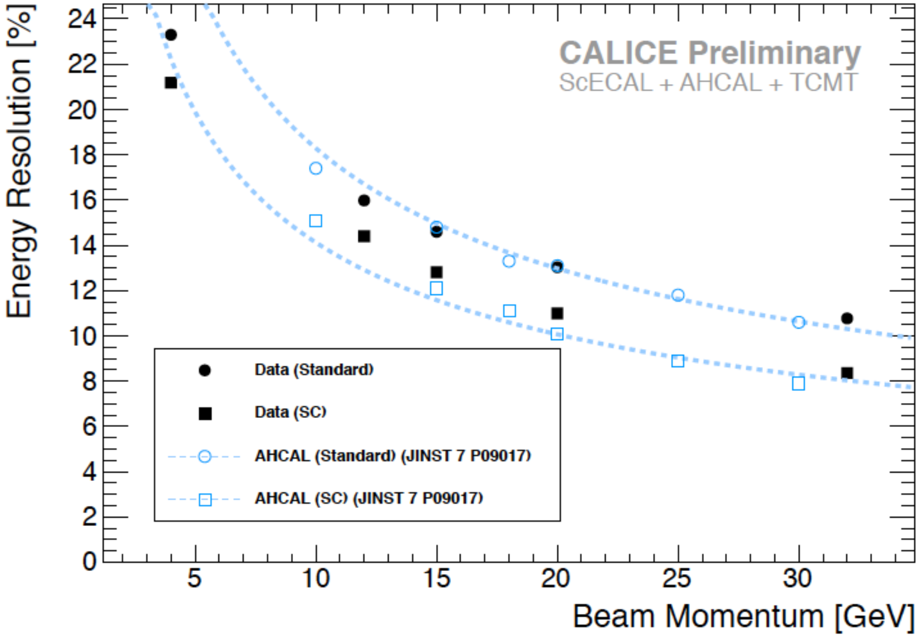
SciECAL AHCAL

CAN-056

Combined scintillator calorimeter system

- in a real calorimeter system, hadrons are not measured purely in HCAL, but in ECAL + HCAL (+tailcatcher)
- ECAL and HCAL typically have different absorber, sampling ratio, active material
- combined system of scintillator-tungsten ECAL + scintillator-steel AHCAL has very similar performance to AHCAL alone

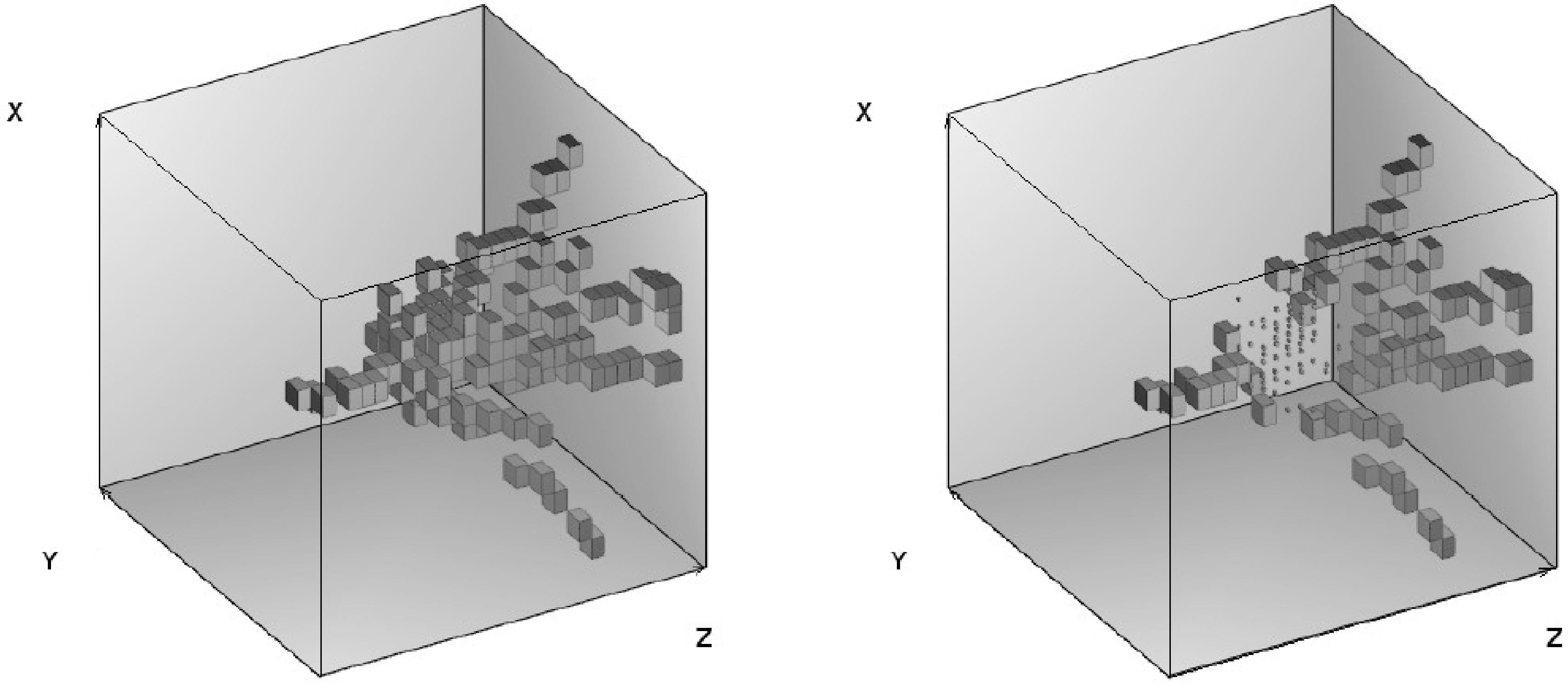




CAN-056

Modeling of hadronic showers

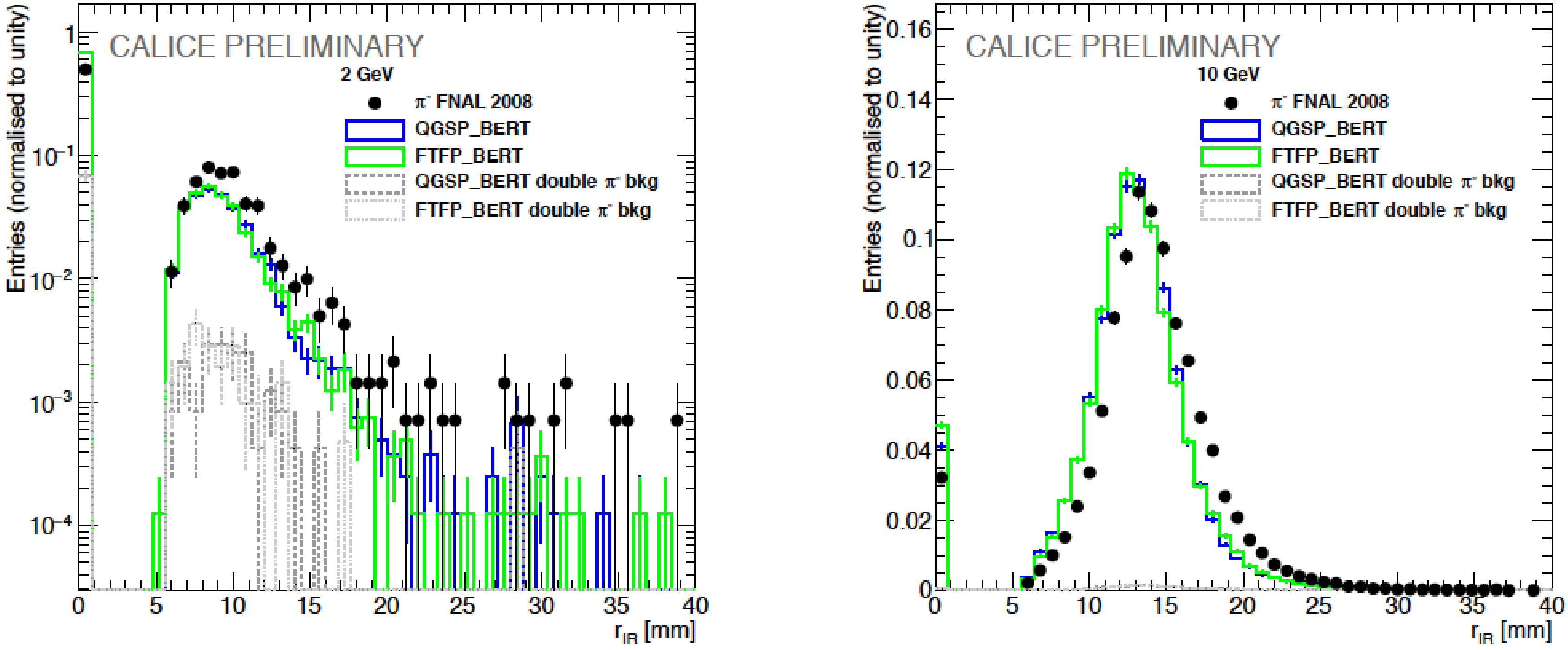
Hadronic Showers in the SiECAL



- very fine SiECAL granularity allows very detailed studies of hadron shower topology
  - characterisation of interaction region of hadronic showers

Hadronic Showers in the SiECAL

CAN-055



- very fine SiECAL granularity allows very detailed studies of hadron shower topology
  - characterisation of interaction region of hadronic showers

Hadronic Showers and Particle Flow Algorithms

- Particle Flow Algorithms are very sensitive to shower shapes
- test of PandoraPFA cluster separation with AHCAL pion shower data:
  - map measured AHCAL test beam pion showers onto ILD geometry
  - test shower separation of a “neutral” hadron (initial track segment removed) of 10 GeV and a charged hadron of 10 or 30 GeV
- good shower energy reconstruction for distances larger than 10 cm
- good description by simulation

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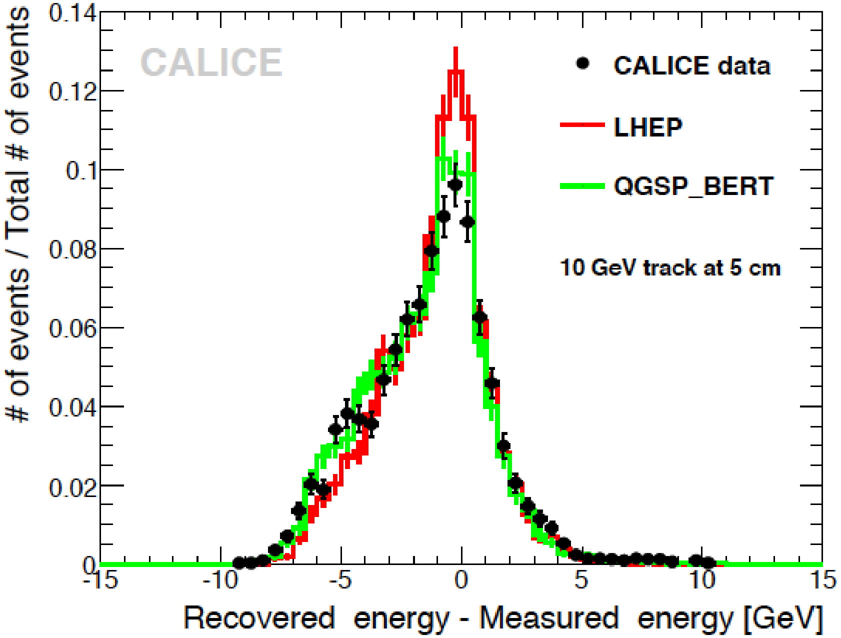

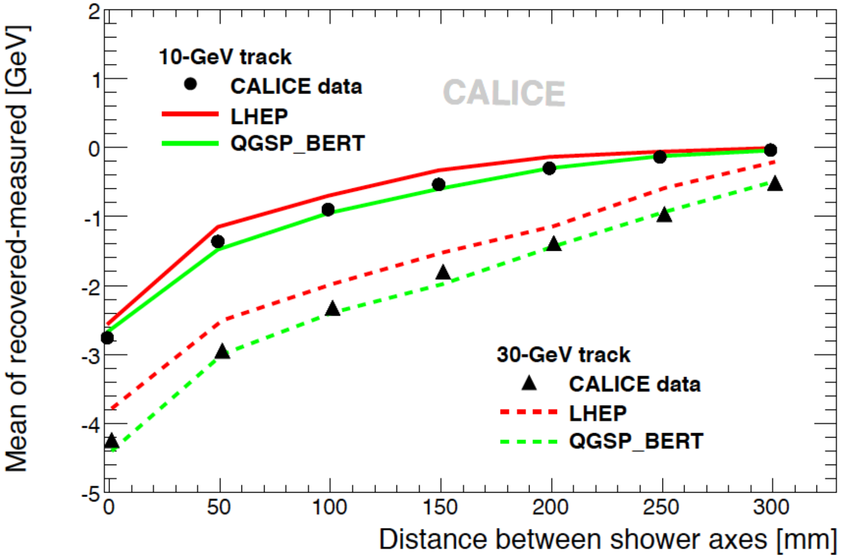

Hadronic Showers and Particle Flow Algorithms

- ArborPFA: particle flow algorithm using the tree-like structure of showers
- test of cluster separation with SDHCAL pion shower data
  - overlay of 2 pion events: 10 GeV “neutral” particle (initial track segment removed) and charged hadron with 10 – 50 GeV at 5 – 30 cm distance
- good efficiency and purity to assign hits to the neutral cluster for distances of 10 cm or more
- important to verify this in simulation!

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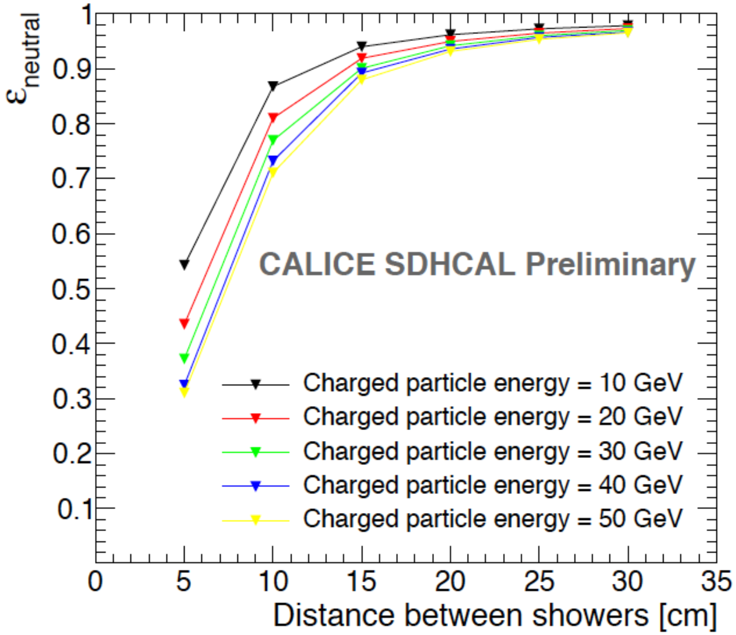
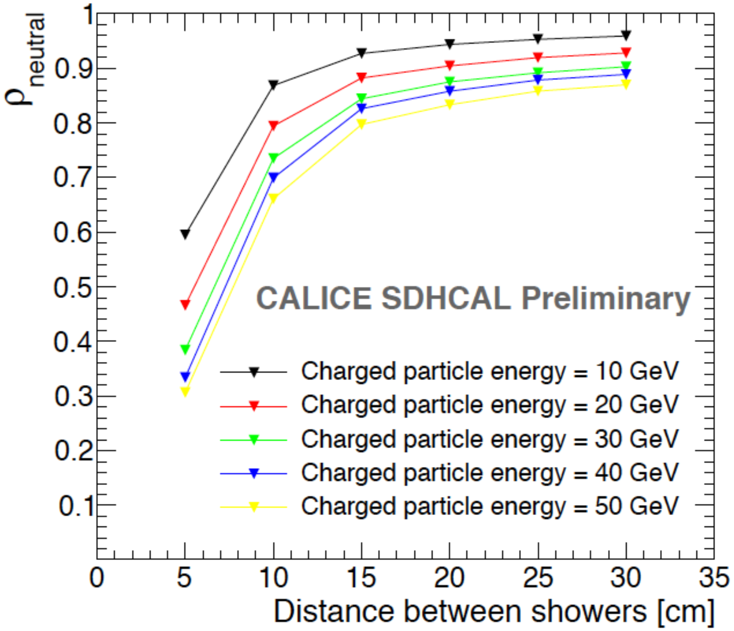
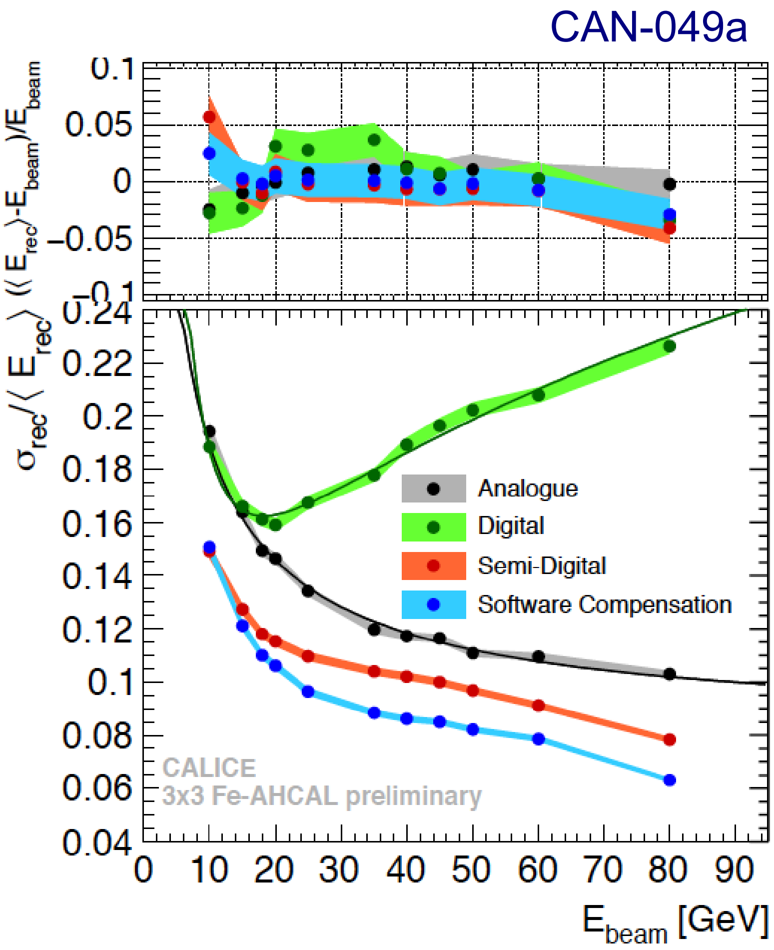




Reconstruction Algorithms and Detector Optimisation

Reconstruction Algorithms

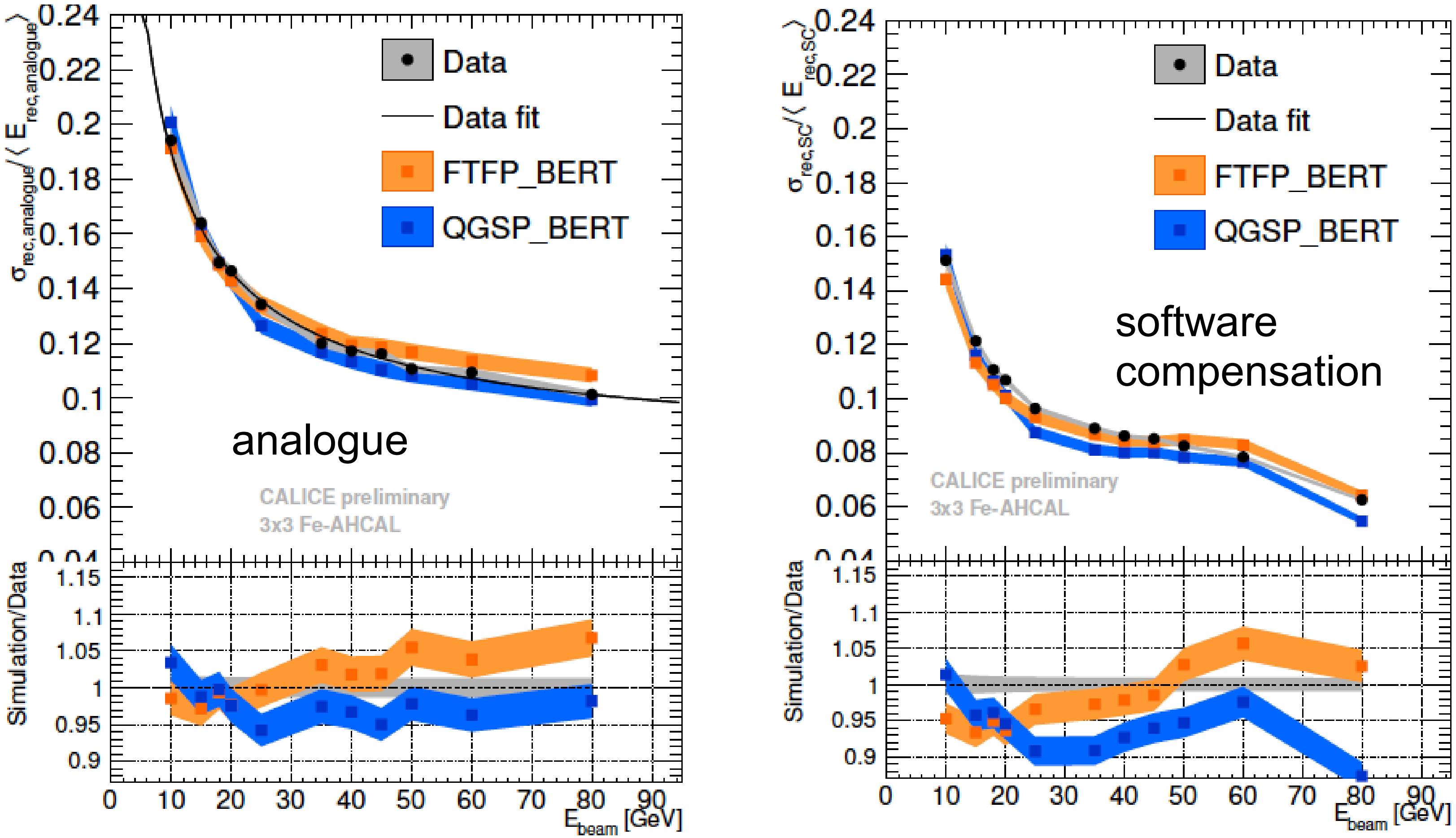
- the 3 HCAL concepts differ in several aspects
  - granularity
  - energy reconstruction method
  - active medium
- all of them influence the energy resolution for single particles and jets
- AHCAL data have been tested with different reconstruction methods
  - analogue summing of is not the best method
  - reconstruction methods that apply weights (semi-digital, software compensation) are better
- results for single particles, need to check with Particle Flow Algorithms applied to jets



Reconstruction Algorithms

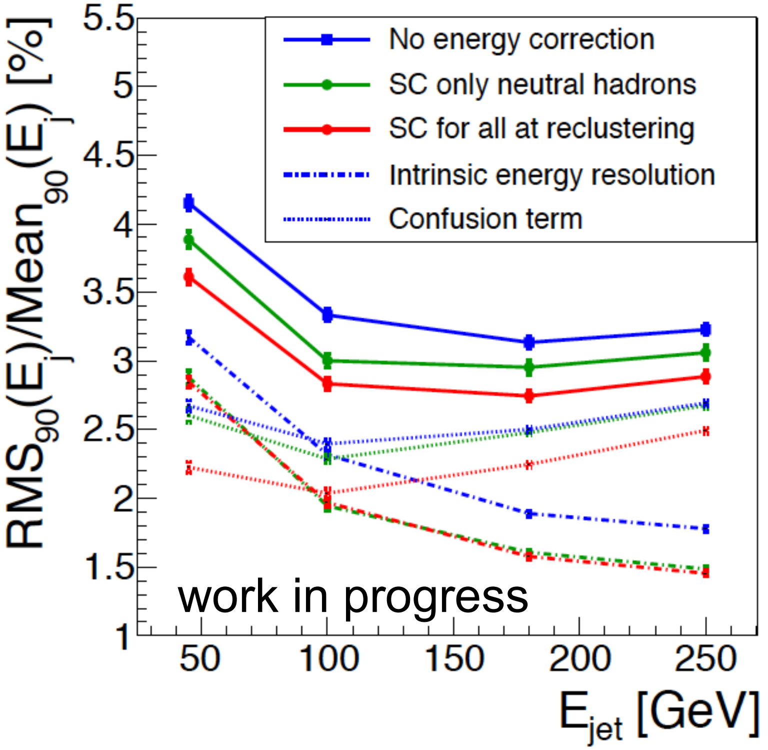
CAN-049a

- all reconstruction methods described within ~5% in simulation



Software Compensation in PandoraPFA

- two steps where software compensation can help
  - during re-clustering (comparison of track and cluster energy for charged particles)
  - in the reconstruction of the energy of neutral hadrons

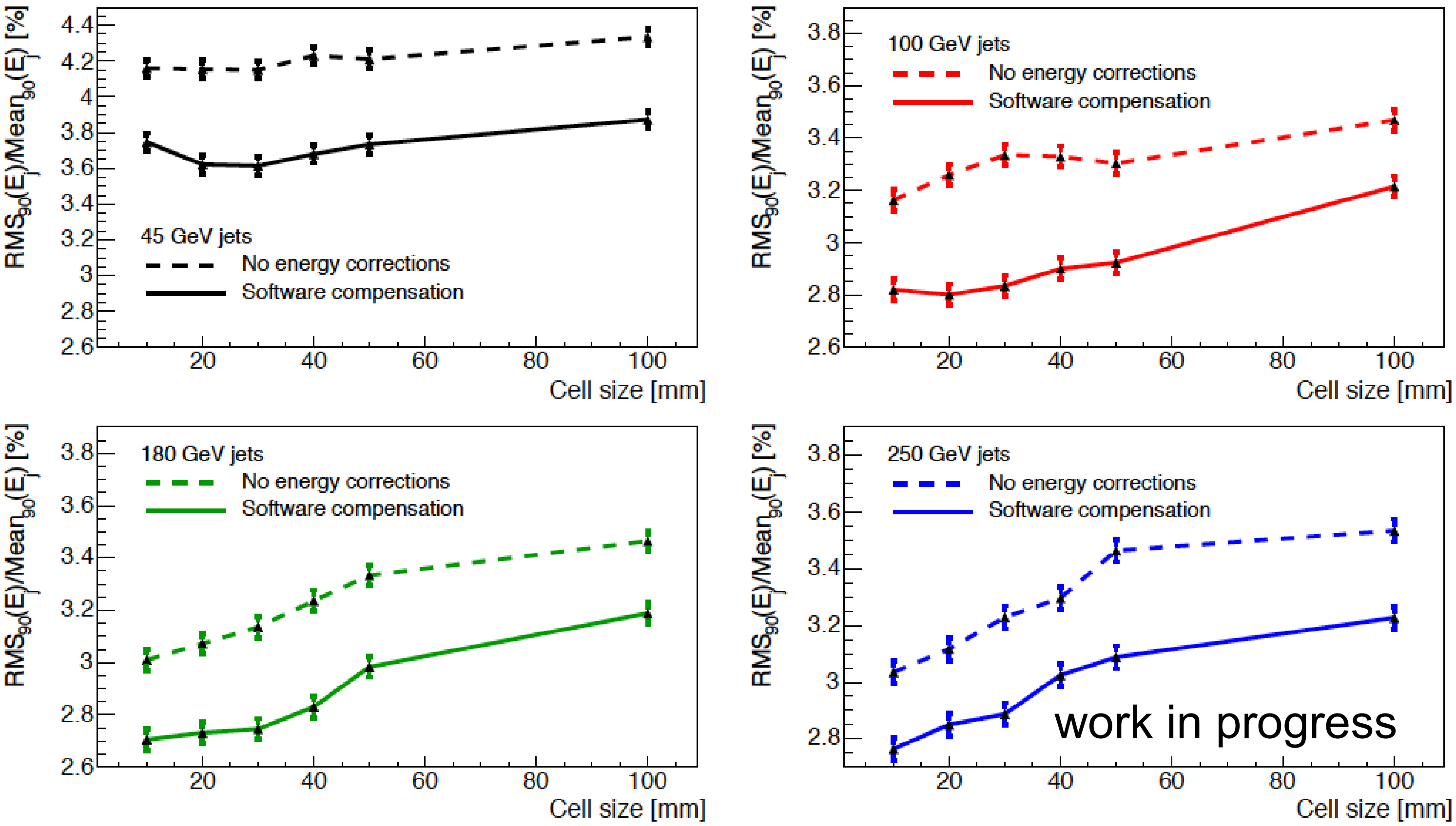


H.L.Tran

- both steps are equally important
  - neutral hadrons important for intrinsic energy resolution
  - re-clustering important to reduce confusion between clusters of neutral and charged hadrons
- effect of software compensation might depend on granularity, so need to check choice of 3*3 cm² cell size
- consider software compensation in detector optimisation

Software Compensation and ILD Detector Optimisation

- software compensation improves jet energy resolution for all cell sizes and all jet energies in a similar way → 3*3 cm² cell size still reasonable
- need to re-check for other detector sizes



work in progress

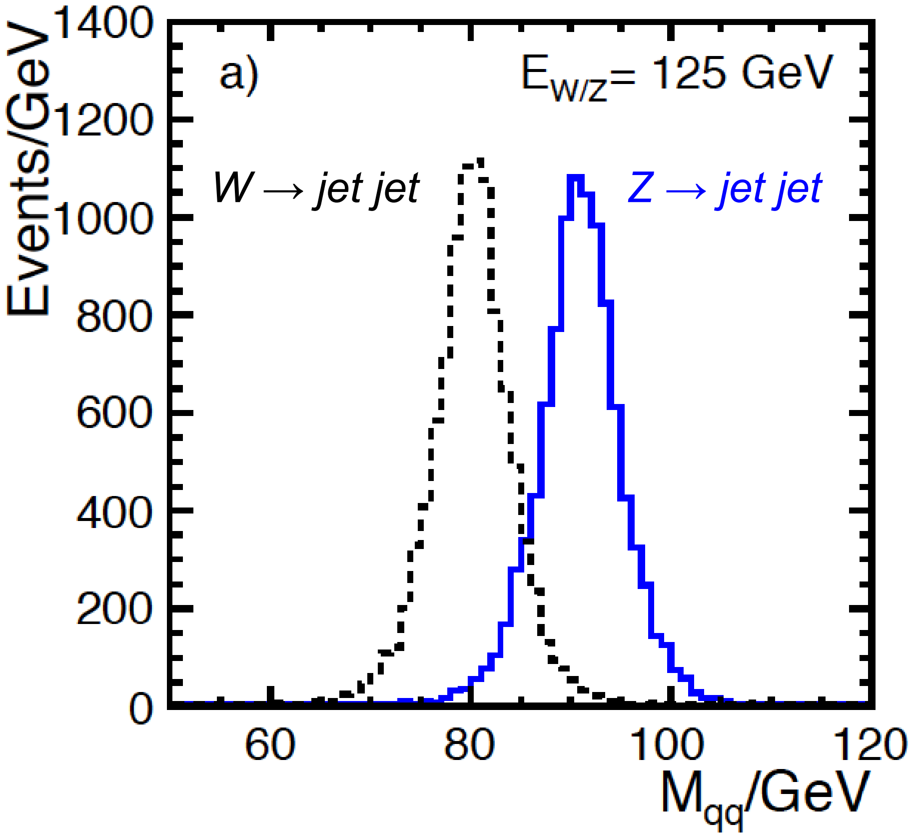
H.L.Tran

Summary

- high granularity of calorimeters leads to new challenges and new opportunities
- simulation
  - tuned digitisation for RPC testbeam prototypes now available
  - validation of Particle Flow Algorithm performance needed
  - ILD SDHCAL simulation should be validated against the testbeam data
- reconstruction algorithms and detector optimisation
  - for AHCAL: software compensation important to reach best energy resolution for single particles and for jets
  - choice of cell size of 3*3 cm² for ILD AHCAL reasonable also with software compensation, needs to be re-checked for other detector size

Backup

Why highly granular calorimeters?

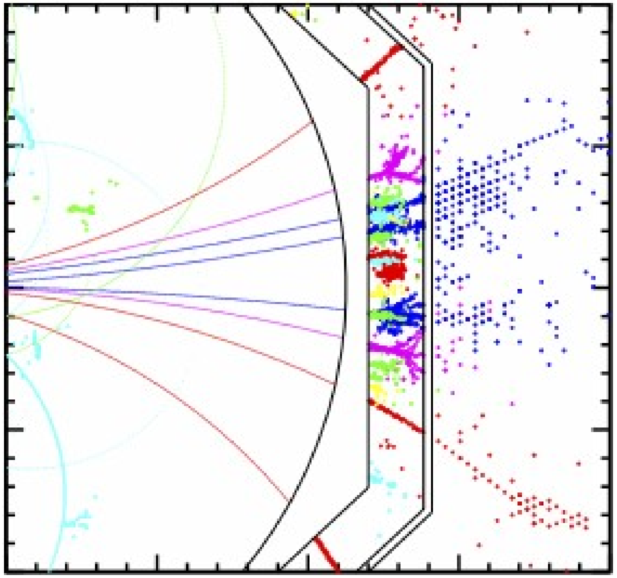


from: M.A. Thomson, Nucl.Instrum.Meth. A611 (2009) 25

- goal: distinguish the decays $Z \to$ *jet jet* and $W \to$ *jet jet* by their reconstructed mass
- Required resolution:
  $\sigma(E_{jet})/E_{jet} \approx$ 3-4%
  for $E_{jet} \approx$ 40 to 500 GeV
- "typical" calorimeter:
  $\sigma(E_{jet})/E_{jet} \approx 60\%/\sqrt{E(\mathrm{GeV})} \oplus 2\%$
  $\Rightarrow \sigma(E_{jet})/E_{jet} \approx 10\%$ at E_{jet} = 50 GeV
- promising solution:
  Particle
  Flow
  Algorithms

Particle Flow Algorithm

- Idea:
  for each individual particle in a jet, use the detector part with the best energy resolution

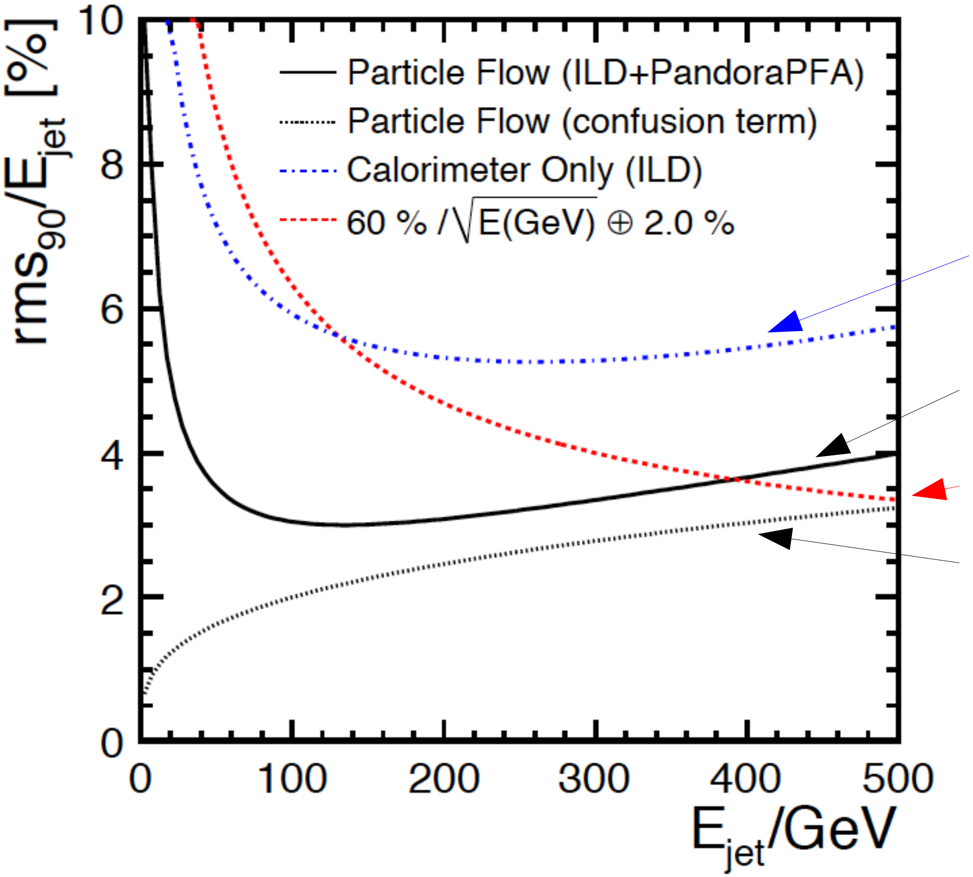


from: M.A. Thomson, Nucl.Instrum.Meth. A611 (2009) 25

- „typical“ jet:

		$(\sigma_{jet})^2$
~ 62% charged particles	tracking	$\approx 0.62\,(\sigma_{tracks})^2$
~ 27% photons	EM calorimeter	$+ 0.27\,(\sigma_{EMCalo})^2$
~ 10% neutral hadrons	HAD calorimeter	$+ 0.10\,(\sigma_{HADCalo})^2$
~~ 1% neutrinos~~		$+ (\sigma_{loss})^2 + (\sigma_{confusion})^2$

Jet Energy Resolution



realistic ILC calorimeter (ILD)

PFA

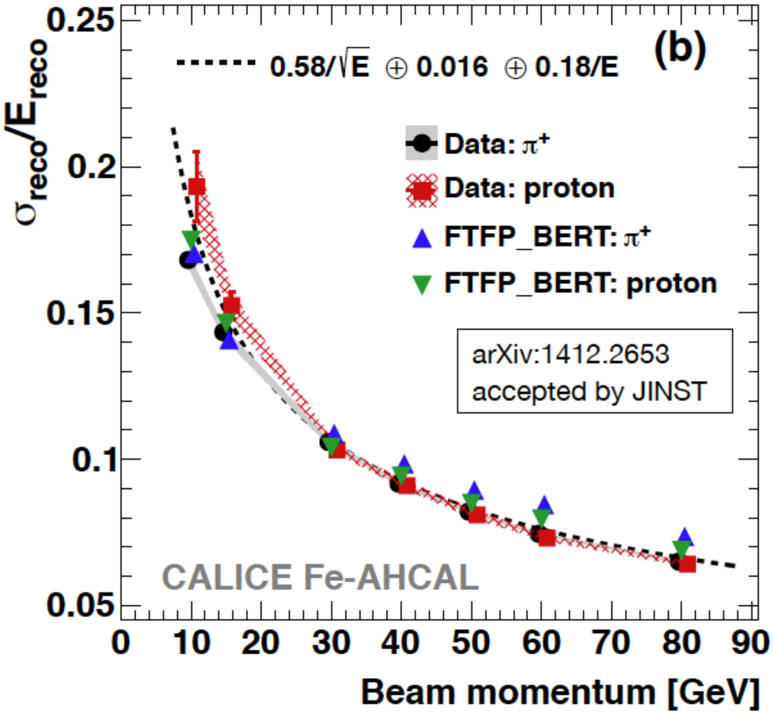
“ideal” traditional HAD calorimeter

„Confusion“: wrong association between tracks and calorimeter clusters, dominates PFA resolution at large energies

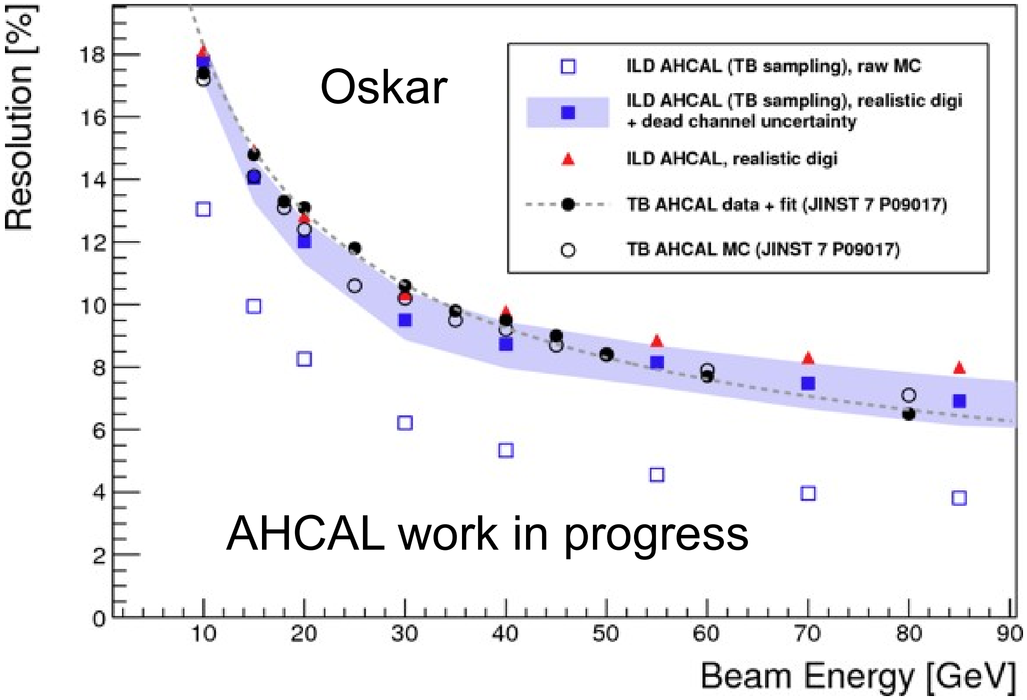
- PFA resolution is clearly better than calorimeter alone
- correct association between tracks and calorimeter clusters is very important ⇒ “imaging” calorimeter with very high granularity

Comparison to Simulation: AHCAL

- description of linearity, resolution and shower shapes shown in many publications
- studies of hadronic shower models (“physics lists”) in GEANT
- recently: show agreement of physics prototype data, prototype simulation and ILD simulation



arXiv:1412.2653
accepted by JINST



Oskar

AHCAL work in progress

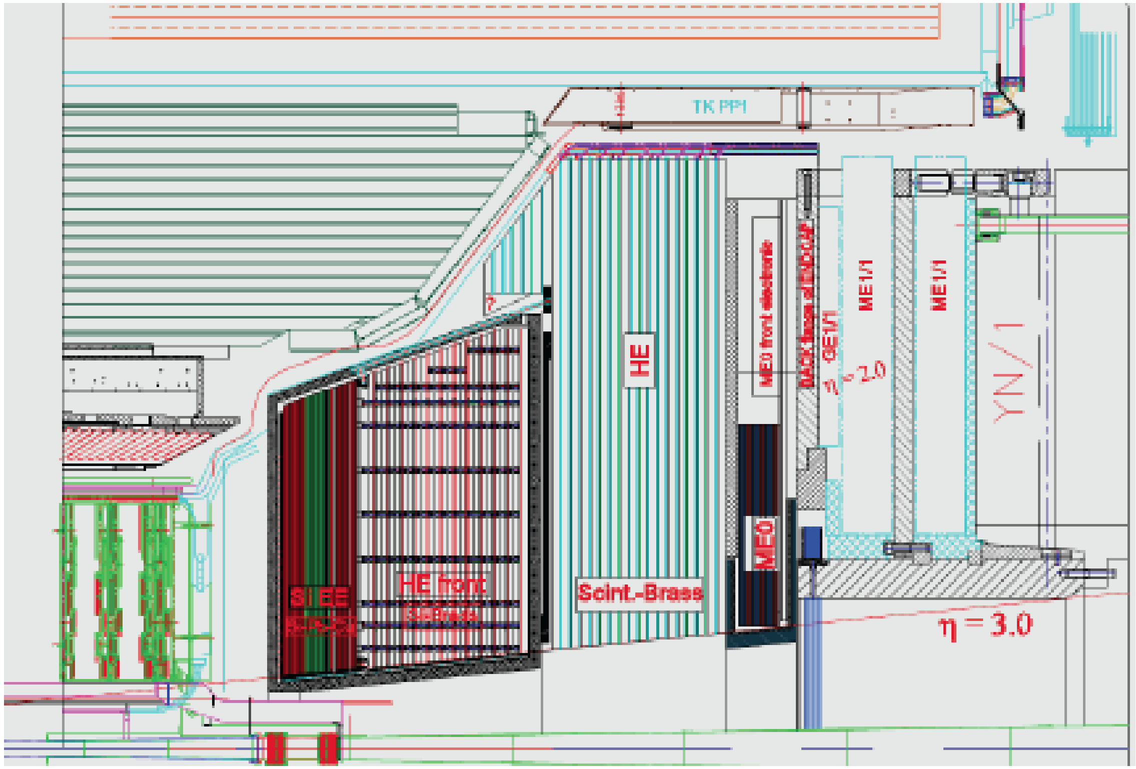
Frank Simon
https://agenda.linearcollider.org/event/6557/session/10/contribution/90/material/slides/0.pdf

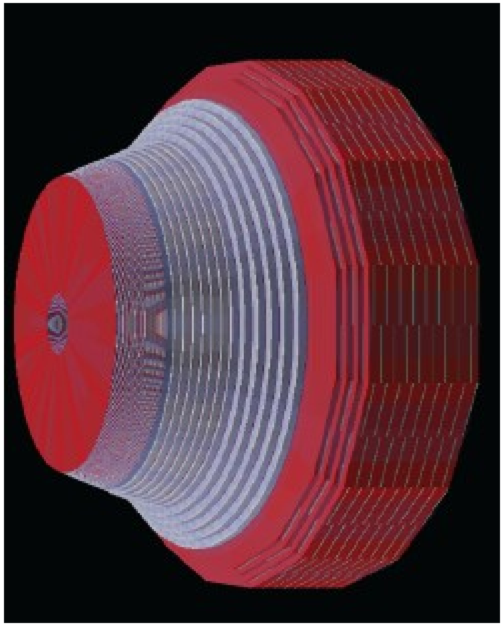
Highly granular calorimeters beyond LC: CMS endcap

- CMS recently decided to chose High Granularity Calorimeter (HGC) as concept for the upgrade of the calorimeter endcap for HL-LHC (2025)
- **Electromagnetic Calorimeter**
  - 30 layers of lead/copper absorber
  - 25 X0
  - 420 m² silicon pad sensors
  - 3.7 M channels
- **Front Hadronic Calorimeter**
  - 12 layers of brass absorber
  - 4 interaction lengths
  - 250 m² silicon pad sensors
  - 1.4 M channels
- **Backing calorimeter**
  - 10 layers
  - 5 interaction lengths
  - lower radiation level allows use of scintillator or MPGDs

high radiation dose
→ rad. hard silicon
→ keep silicon at -35°C

Highly granular calorimeters beyond LC: CMS endcap





hexagonal sensors