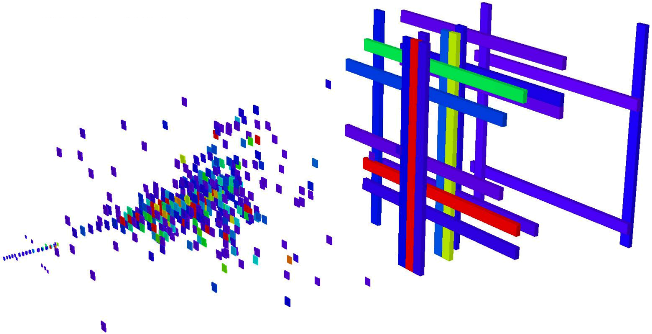
Software compensation in a combined ECAL and HCAL system

Yasmine Israeli for the CALICE collaboration
January 25, 2018



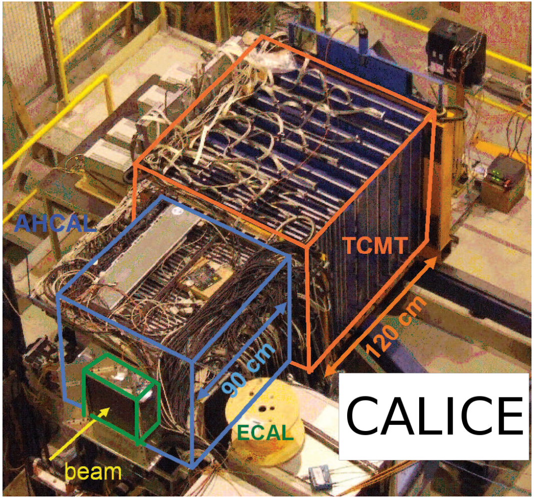
Testbeam Analysis of a Full Calorimeter System

CALICE physics prototypes:
⊛ Si-W ECAL + AHCAL + TCMT

Testbeam experiments:
⊛ CERN 2007
⊛ FNAL 2008

Datasets:
⊛ π^- 4-80 GeV (10-80 GeV, 4-60 GeV)

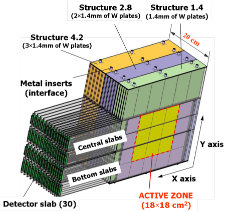
Reconstruction Methods:
⊛ Standard reconstruction
⊛ Software compensation (SC)



Full Calorimeter Systems

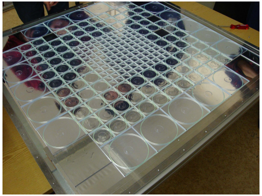
Si-W ECAL Silicon Tungsten Electromagnetic Calorimeter

1.4mm, 2.8mm, 4.2mm W
Silicon sensors
24.6 χ_0
9720 channels



AHCAL Analog Hadronic Calorimeter

21mm Fe
Scintillators & SiPMs
5.3 λ_I
7608 channels

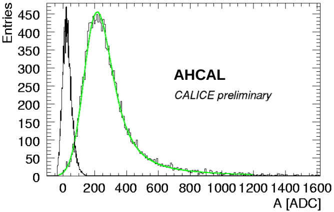


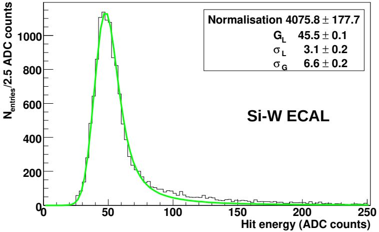
TCMT Tail Catcher Muon Tracker

21mm, 105mm Fe
Scintillators & SiPMs
5.8 λ_I
320 channels

MIP Calibration

- To equalize the response of the cells in each sub detector
  → a cell-to-cell calibration from ADC counts to MIPs unit





- For each channel:
  - Clean muon sample
  - The energy spectrum is fitted with a convolution of a Landau distribution and a Gaussian function
  - Most probable value⇒MIP calibration factor

Standard Energy Reconstruction

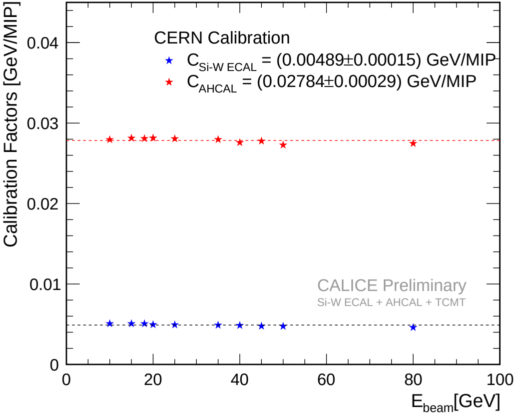
$$E_{\text{reco}}^{\text{event}} = C_{\text{ECAL}} \cdot \left(\sum_{j}^{\text{hits}} E_j^{\text{ECAL}} [\text{MIP}] c_t \right) + C_{\text{AHCAL}} \cdot \left(\sum_{j}^{\text{hits}} E_j^{\text{AHCAL}} [\text{MIP}] + \sum_{j}^{\text{hits}} E_j^{\text{TCMT}} [\text{MIP}] c_t \right)$$

C_{ECAL}, C_{AHCAL} - **calibration factors MIP to GeV**:

1. Calibration factors for each beam energy:

$$\chi^2 = \sum_{\text{events}} \frac{\left(E_{\text{reco}}^{\text{event}} - E_{\text{beam}}\right)^2}{(\sigma_E)^2}.$$

2. Averaging to remove possible energy dependence.



Standard Energy Reconstruction

$$E_{\text{reco}}^{\text{event}} = C_{\text{ECAL}} \cdot \left(\sum_{j}^{\text{hits}} E_j^{\text{ECAL}} [\text{MIP}] c_t \right) + C_{\text{AHCAL}} \cdot \left(\sum_{j}^{\text{hits}} E_j^{\text{AHCAL}} [\text{MIP}] + \sum_{j}^{\text{hits}} E_j^{\text{TCMT}} [\text{MIP}] c_t \right)$$

c_t for the different absorber thickness.

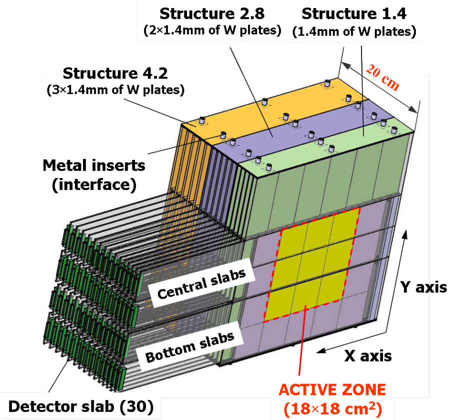
Each hit is weighted by the amount of absorber material in the respective layer

Si-W ECAL:

- layers 1-10: 1.4 mm W → $c_t = 1$
- layers 11-20: 2.8 mm W → $c_t = 2$
- layers 21-30: 4.2 mm W → $c_t = 3$

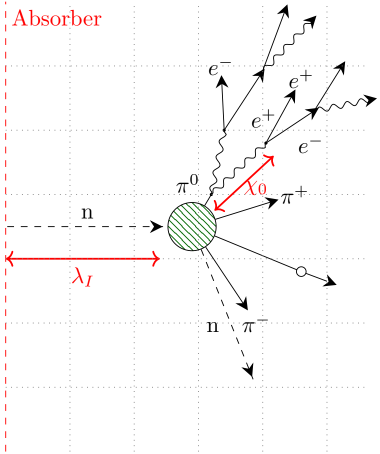
TCMT:

- layers 1-8: 19 mm Fe → $c_t = 1$
- layers 9-16: 105 mm Fe → $c_t = 5$



Compensation

- Non-compensating calorimeters
- Mean deposition of electrons higher than hadrons: $\frac{e}{h} > 1$
- Fluctuation of EM fraction reduce energy resolution for hadrons



Software Compensation:

Different local energy density of electromagnetic and hadronic sub-showers

- Each shower-hit in the reconstruction is weighted according to the local energy density
- Expected:

↪ lower density hits (mostly hadronic) → weights>1

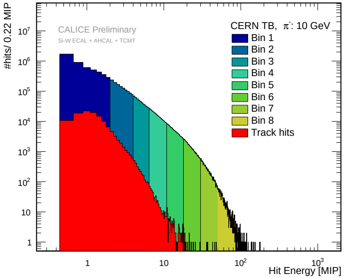
↪ higher density hits (mostly EM) → weights<1

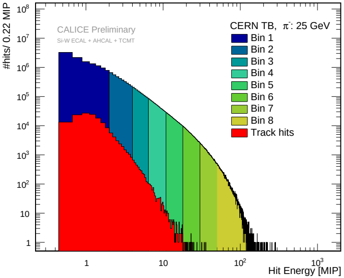
↪ improving the energy resolution!

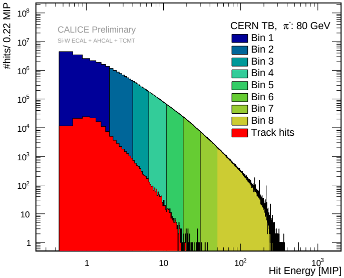
Software Compensation Energy Reconstruction

- Shower hit energy in 8 bins (primary track via standard reconstruction)

  For each bin:
  - Summing the hit energies
  - Applying a weight







Software Compensation Weights

⊛ Bin weights are parametrised with particle energy $\omega_j(E)$

⟶ 2^{nd} order polynomials

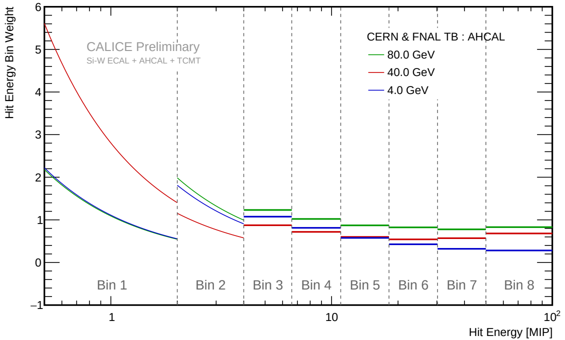
⟶ 3 parameters for each bin: a_j, b_j, c_j

in total 51 parameters

$$\chi^2 = \sum_{\text{events}} \frac{\left(E^{\text{event}}_{\text{Full SC}} - E^{\text{event}}_{\text{beam}}\right)^2}{\left(55\%\sqrt{\text{GeV}}\right)^2 \cdot E^{\text{event}}_{\text{beam}} \cdot N^{\text{event}}_{\text{beam}}}$$

$E = E_{\text{beam}}$ in weights optimization

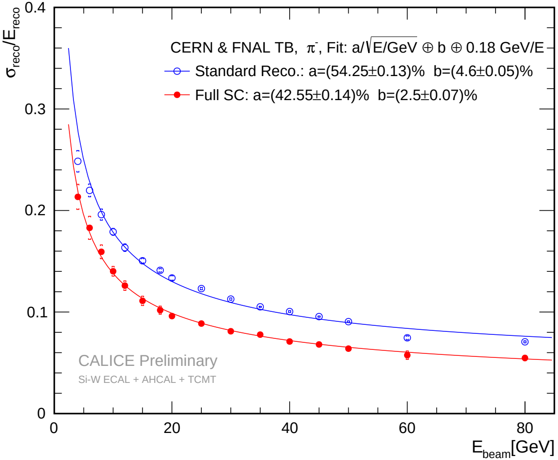
$E = E_{\text{reco}}$ in SC energy reconstruction

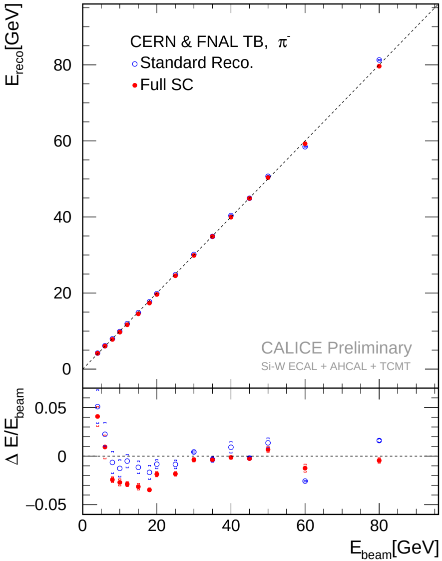


- Binary reconstruction in bins 1-2 to suppress Landau fluctuations

Energy Resolution and Linearity

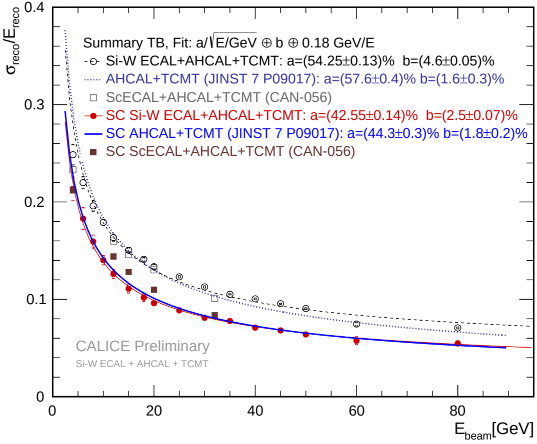
Up to 30% improvement





Comparison with Previous Analyses

- ⊛ AHCAL+TCMT : JINST 7 P09017
  - ▷ Showers start: first 5 layers of AHCAL
  - ▷ SC applied to AHCAL+TCMT
- ⊛ ScECAL+AHCAL+TCMT : CAN-056
  - ▷ Scintillator+SiPMs system
  - ▷ Showers start:
    ScECAL till 5th layer of AHCAL
  - ▷ SC applied to ScECAL+AHCAL+TCMT

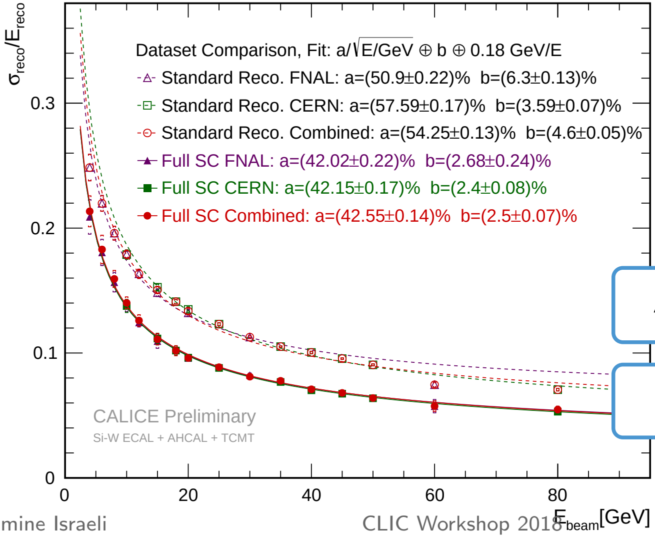


Similar performance despite the:

- ▷ different absorber material (W, Fe)
- ▷ different structure (Si-W ECAL)
- ▷ different readout techniques (Si sensor,Scintillators+SiPMs)

Detector Performance in Different Beam Periods

Reconstruction of different datasets **separately**



CERN 2007
FNAL 2008
CERN+FNAL

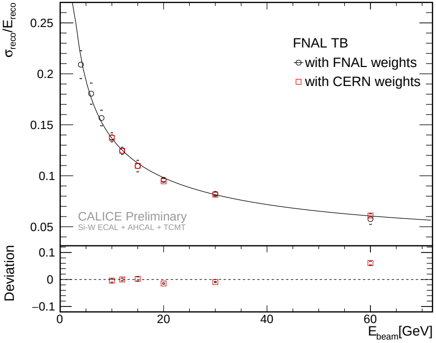
Agreement within 2.5% for datasets

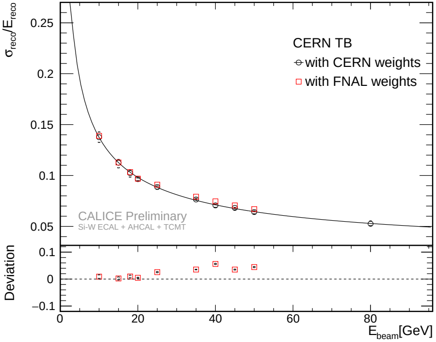
Detector performance is consistent

Systematic Test of the SC Method Robustness

Application of Weights to Different Beam Periods:

- Optimizing SC weights with one testbeam dataset (CERN/FNAL TB)
- Implementing these weights on a different testbeam dataset (FNAL/CERN TB)



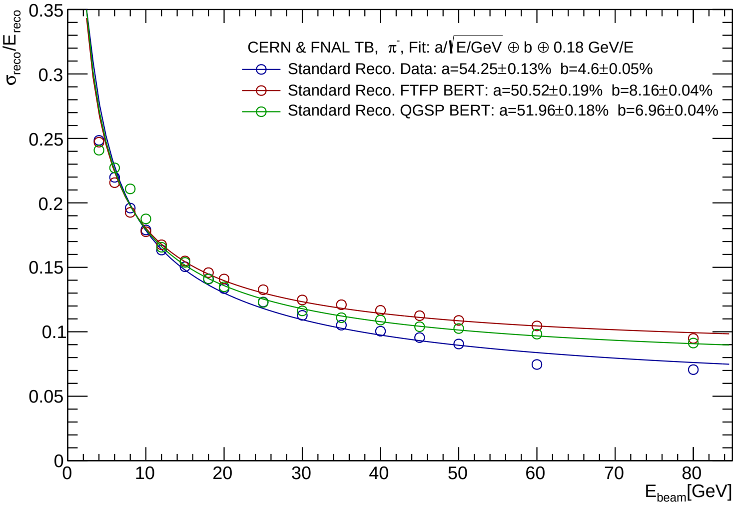


Deviation < 2%
(excluding 60 GeV with ~6%)

Deviation with energy dependence
up to ~6%

Comparison with Simulations : Energy Resolution

Optimizing weights for data and for MC

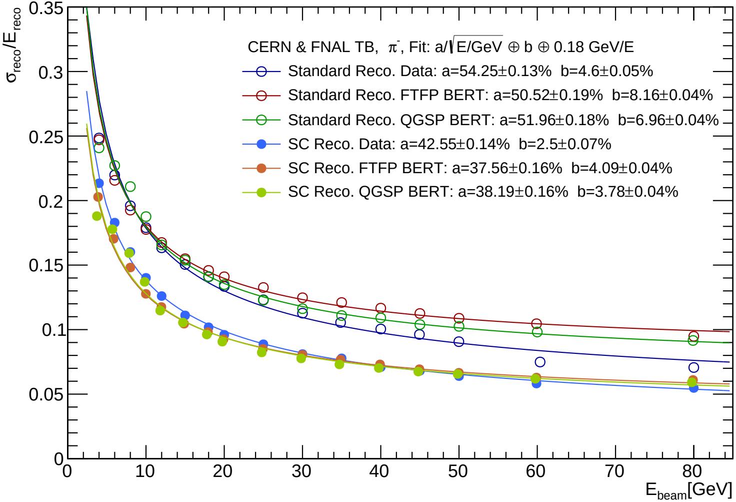


GEANT4 10.1:
FTFP BERT
QGSP BERT

Standard reco.: an energy dependent deterioration of the simulation resolution

Comparison with Simulations : Energy Resolution

Optimizing weights for data and for MC

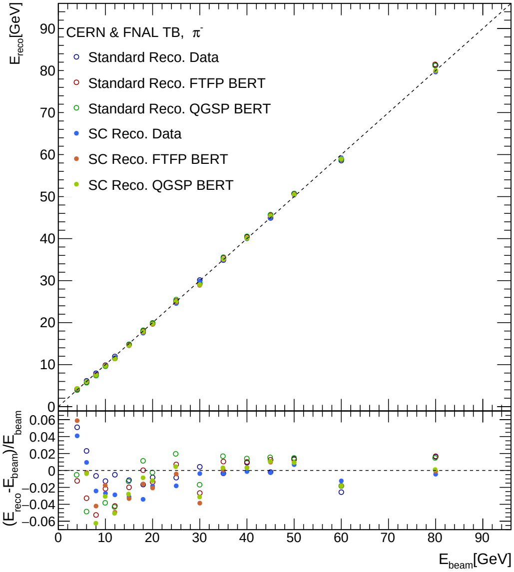


GEANT4 10.1:
FTFP BERT
QGSP BERT

Standard reco.: an energy dependent deterioration of the simulation resolution

SC reco.: similar resolutions between 30-80 GeV

Comparison with Simulations : System Linearity



GEANT4 10.1:
FTFP BERT
QGSP BERT

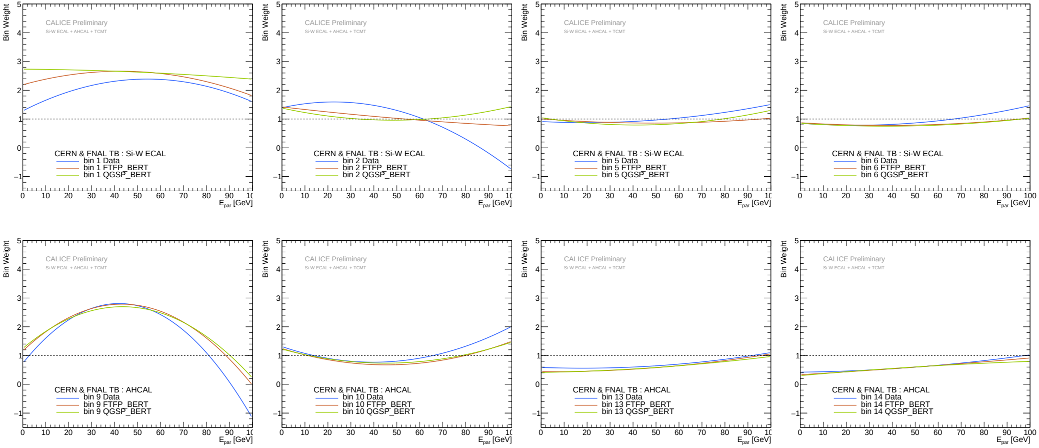
- ⋆ All the relative deviation are < 6%
- ⋆ From 35 GeV:
  SC results are more compatible

Comparison with Simulations : SC weights

Weights as a function of the beam energy for data, FTFP BERT and QGSP BERT

Si-W ECAL : discrepancies for the first two bins

AHCAL : reasonable agreement between the weights



SC in Different Detectors

ECAL SC

SC in the Si-W ECAL

24 parameters

HCAL SC

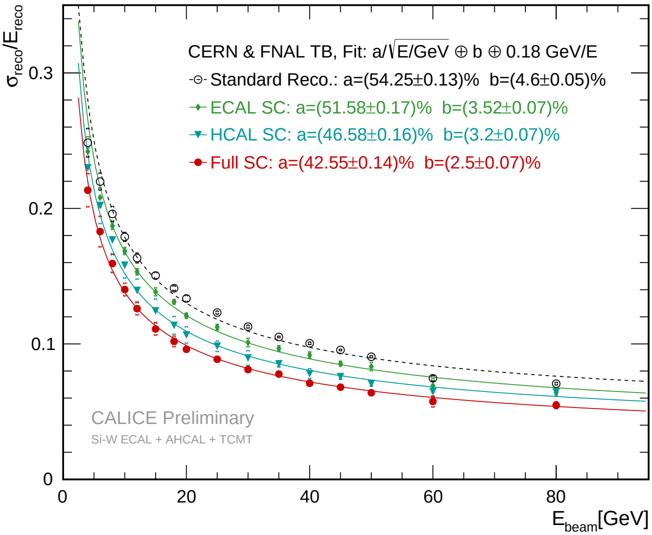
SC in the AHCAL & TCMT

27 parameters

Full SC

SC in 3 detectors

51 parameters

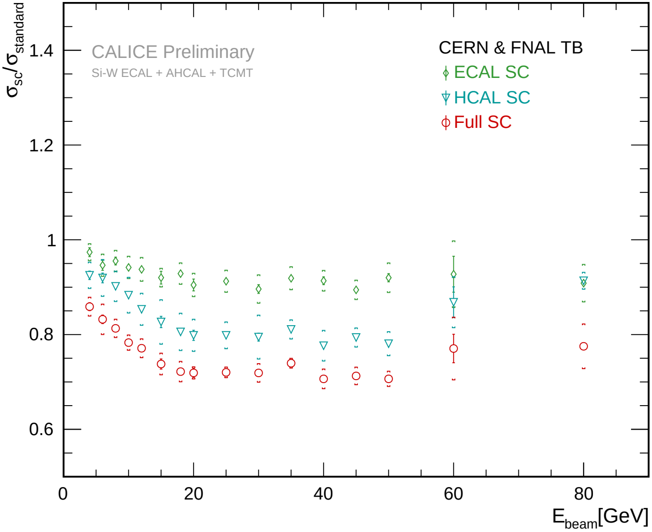


SC in Different Detectors

ECAL SC
SC in the Si-W ECAL
24 parameters
→ up to 8% improvement

HCAL SC
SC in the AHCAL & TCMT
27 parameters
→ up to 23% improvement

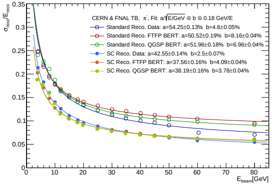
Full SC
SC in 3 detectors
51 parameters
→ up to 30% improvement



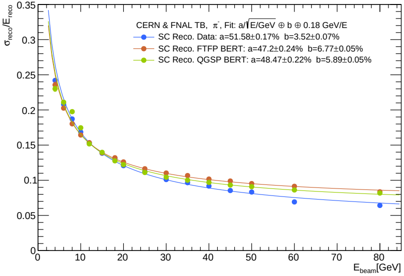
Comparison with Simulations : ECAL & HCAL SC

- Full SC scheme shows better agreement between data and simulation results in the higher energy range

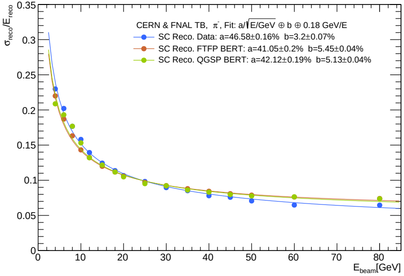
Full SC



ECAL SC



HCAL SC

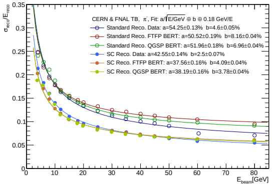


Comparison with Simulations : ECAL & HCAL SC

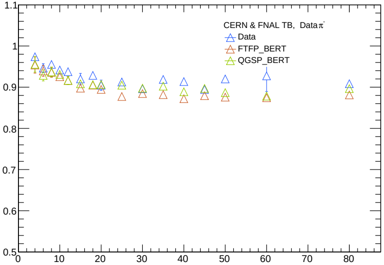
- Full SC scheme shows better agreement between data and simulation results in the higher energy range
- Resolution improvement up to:

	ECAL SC	HCAL SC
FTFP BERT	14%	28%
QGSP BERT	12%	25%
Data	8%	23%

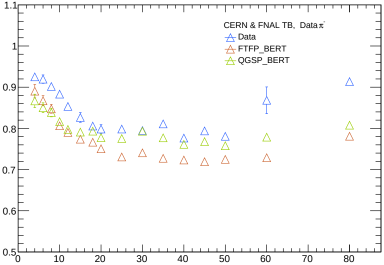
Full SC



ECAL SC



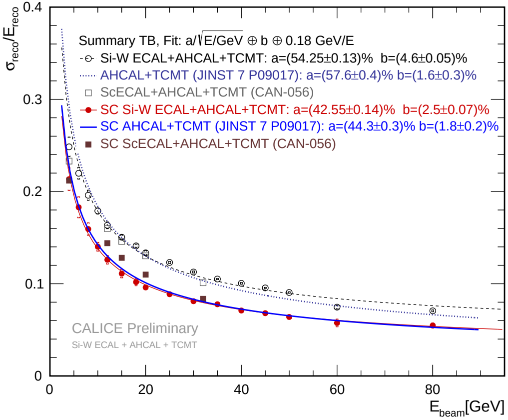
HCAL SC



Summary

☑Analysis of CALICE high granularity combined full calorimeter system

☑Similar performance as "less complexed" previous analyses



☑Robustness test of the SC method

☑Data vs MC: agreement with
Full SC reconstruction
(from ~ 30 GeV)

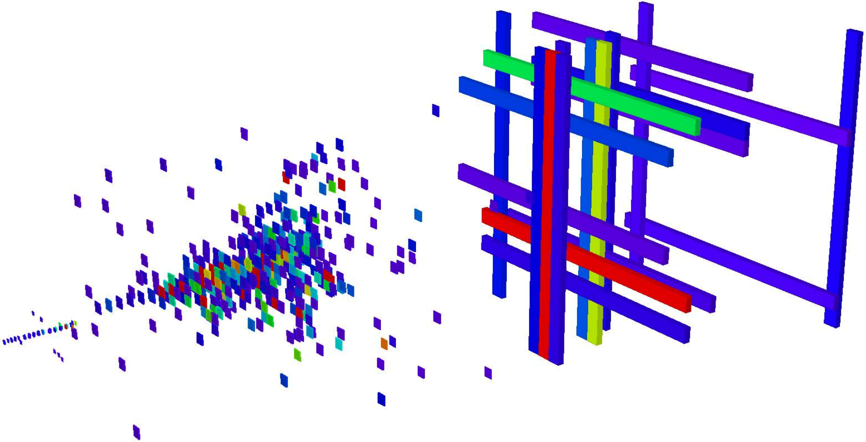
☑Applying SC to different detectors
energy resolution improvement:

Full SC - up to 30%

HCAL SC - up to 23%

ECAL SC - up to 8%

Thank you for your attention ☺



BACKUP

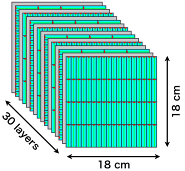
Testbeam Analyses

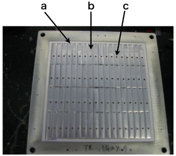
Full calorimeter systems of CALICE physics prototypes
$\circledast$ ScECAL + AHCAL + TCMT
Datasets from testbeam experiments:
π^- FNAL 2009, 4-32 GeV

Full Calorimeter Systems

ScECAL
Scintillator
Electromagnetic
Calorimeter

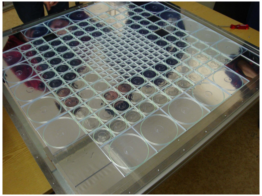
3.5mm W
Scintillators & SiPMs
21.3 χ_0
2160 channels





AHCAL
Analog
Hadronic
Calorimeter

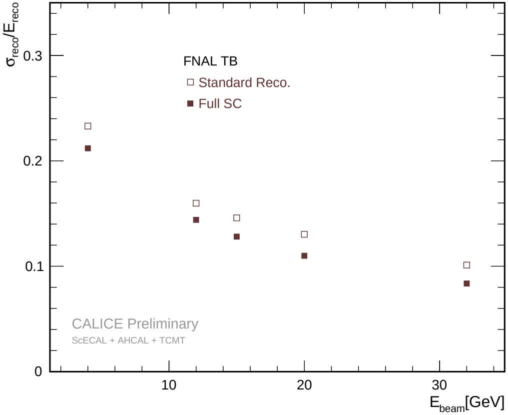
21mm Fe
Scintillators & SiPMs
5.3 λ_I
7608 channels



TCMT
Tail Catcher
Muon Tracker

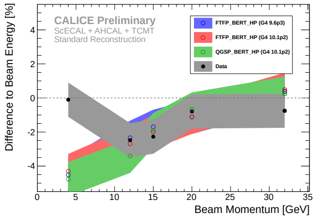
21mm, 105mm Fe
Scintillators & SiPMs
5.8 λ_I
320 channels

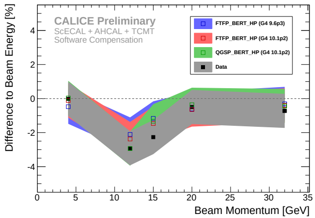
Energy Resolution and Linearity



FULL SC up to 20% improvement.

Deviations from $E_{beam} < 4\%$.





Software Compensation Weights

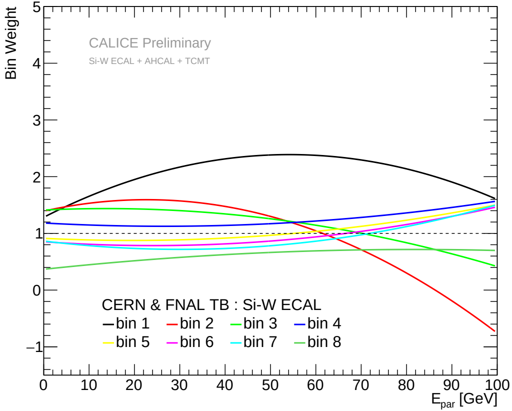
Bin weights parametrised with beam energy:
2^{nd} order Chebyshev polynominal

$$\omega_j(E) = a_j + b_j \times \frac{E}{S} + c_j \times \left(2 \times \left(\frac{E}{S}\right)^2 + 1\right)$$

$E = E_{\mathrm{beam}}$ in weights optimization
$E = E_{\mathrm{reco}}$ in SC energy reconstruction
$S = 100\ GeV$ scale factor to preserve orthogonality

⊛ 3 energy independent parameters $a_j, b_j, c_j,$

$$\chi^2 = \sum_{\mathrm{events}} \frac{\left(E^{\mathrm{event}}_{\mathrm{Full\ SC}} - E^{\mathrm{event}}_{\mathrm{beam}}\right)^2}{\left(55\%\sqrt{\mathrm{GeV}}\right)^2 \cdot E^{\mathrm{event}}_{\mathrm{beam}} \cdot N^{\mathrm{events}}_{\mathrm{beam}}}. \quad (1)$$



SC Schemes

FULL SC in all 3 detectors (51 parameters):

$$E_{\text{Full SC}}^{\text{event}} = C_{\text{Si-W ECAL}} \cdot \left(\sum_{i}^{\text{bins}} \alpha_i \left(E \right) \cdot E_i^{\text{Si-W ECAL}} + E_{\text{track}}^{\text{Si-W ECAL}} \right) + C_{\text{AHCAL}} \cdot \left(\sum_{i}^{\text{bins}} \beta_i \left(E \right) \cdot E_i^{\text{AHCAL}} + E_{\text{track}}^{\text{AHCAL}} + \gamma \left(E \right) \cdot E_{\text{sum}}^{\text{TCMT}} \right)$$

(2

HCAL SC in AHCAL and TCMT (27 parameters):

$$E_{\text{HCAL SC}}^{\text{event}} = C_{\text{Si-W ECAL}} \cdot \left(\sum_{j}^{\text{hits}} E_j^{\text{Si-W ECAL}} \right) + C_{\text{AHCAL}} \cdot \left(\sum_{i}^{\text{bins}} \beta_i \left(E \right) \cdot E_i^{\text{AHCAL}} + E_{\text{track}}^{\text{AHCAL}} + \gamma \left(E \right) \cdot E_{\text{sum}}^{\text{TCMT}} \right) \tag{3}$$

ECAL SC in Si-W ECAL (24 parameters):

$$E_{\text{ECAL SC}}^{\text{event}} = C_{\text{Si-W ECAL}} \cdot \left(\sum_{i}^{\text{bins}} \alpha_i \left(E \right) \cdot E_i^{\text{Si-W ECAL}} + E_{\text{track}}^{\text{Si-W ECAL}} \right) + C_{\text{AHCAL}} \left(\sum_{j}^{\text{hits}} E_j^{\text{AHCAL}} + \sum_{j}^{\text{hits}} E_j^{\text{TCMT}} \right) \tag{4}$$

Reducing Landau Fluctuations

Landau fluctuations of particle hits also decrease the energy resolution

we assume: hits from **one or few** particles in the lower energies
(in this case the first two bins)

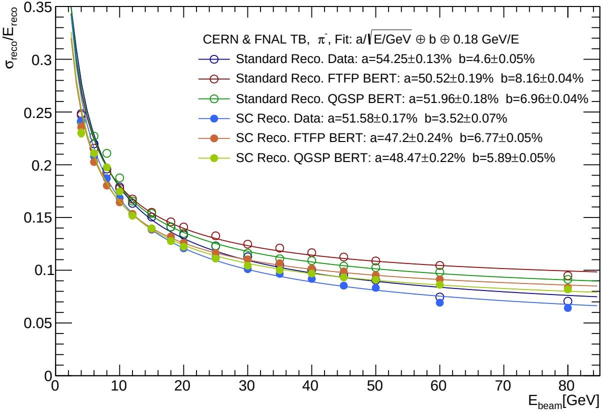
⟹ set constant energy contributions from these bins

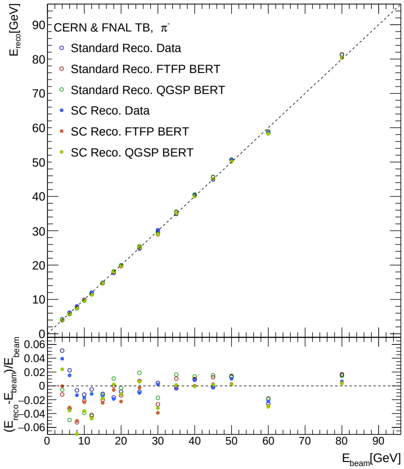
---

in practice:

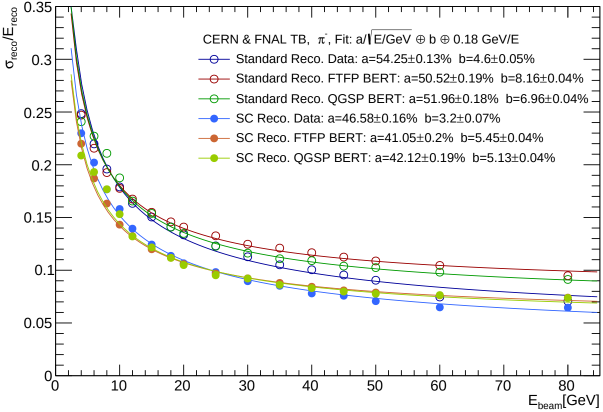
▷ Counting the number of hits instead of summing hit energies.
▷ Weighting to the corresponding energy.
▷ In visualization: weights are normalized to the hit energy
(to be compatible with the other weights).

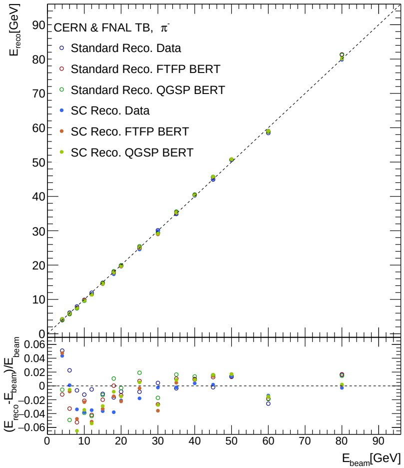
Comparison with Simulations : ECAL SC





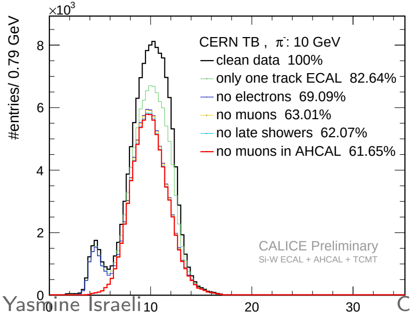
Comparison with Simulations : HCAL SC





Event Selection

- Clean data
- Reject incomplete showers: First Had. Interaction (FHI) layer < 55
- Remove contamination of:
    - **multi-particle events** - only one particle entering ECAL via clustering
    - **electron events** - FHI layer > 6
    - **muon events**
        - only events with reconstructed FHI layer
        - cut on $E_{\mathrm{reco}}^{\mathrm{event}}$ for low energy muons
        - reject events with additional muons entering directly to AHCAL



Clean data:

- Beam trigger
- Removing empty or not identified events
- Removing events where ECAL fails
- Removing multi-particle events
- Cherenkov counter in FNAL for e^-

Fit

A Gaussian fit in two stages:

① full range μ, σ

② interval of $\pm 2\sigma$ around μ

$\Rightarrow$ reconstructed energy $E_{\text{reco}} = \widetilde{\mu}$

energy resolution $\frac{\sigma_{\text{reco}}}{E_{\text{reco}}} = \frac{\widetilde{\sigma}}{\widetilde{\mu}}$