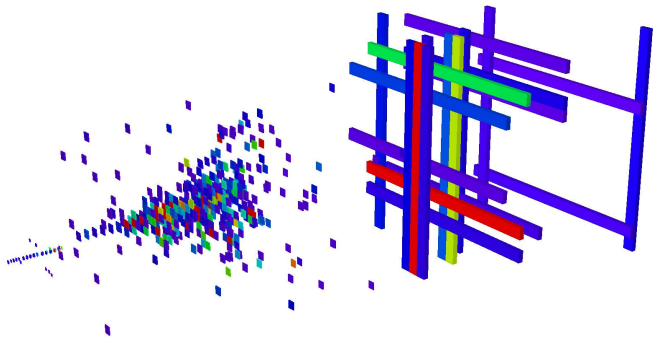
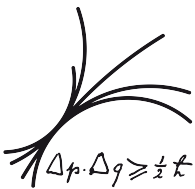
Energy Reconstruction of Hadrons in highly granular combined ECAL and HCAL systems

Yasmine Israeli for the CALICE collaboration
October 24, 2017





Testbeam Analyses

Full calorimeter systems of CALICE physics prototypes

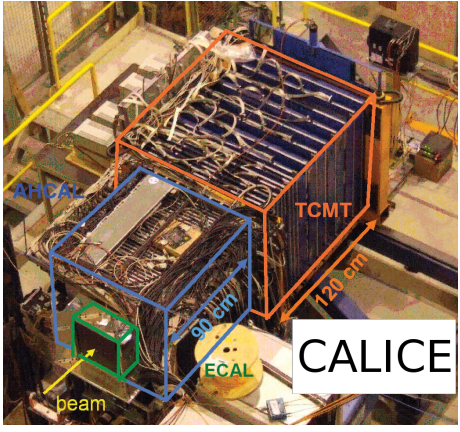
- Si-W ECAL + AHCAL + TCMT
- ScECAL + AHCAL + TCMT

Datasets from testbeam experiments:

- π^- CERN 2007, 10-80 GeV
- π^- FNAL 2008, 4-60 GeV
- π^- FNAL 2009, 4-32 GeV

Energy reconstruction:

- Standard reconstruction
- Software compensation (SC)

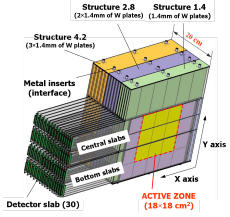


Full Calorimeter Systems

Si-W ECAL

Silicon Tungsten Electromagnetic Calorimeter

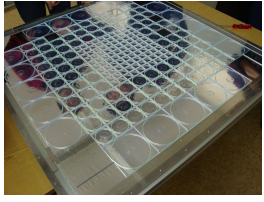
1.4mm, 2.8mm, 4.2mm W
Silicon sensors
24.6 χ_0
9720 channels



AHCAL

Analog Hadronic Calorimeter

21mm Fe
Scintillators & SiPMs
5.3 λ_I
7608 channels



TCMT

Tail Catcher Muon Tracker

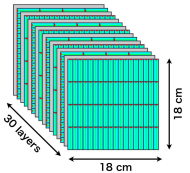
21mm, 105mm Fe
Scintillators & SiPMs
5.8 λ_I
320 channels

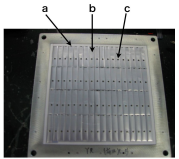
Full Calorimeter Systems

ScECAL

Scintillator Electromagnetic Calorimeter

3.5mm W
Scintillators & SiPMs
21.3 χ_0
2160 channels





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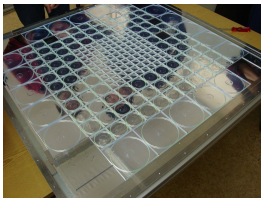

TCMT

Tail Catcher Muon Tracker

21mm, 105mm Fe
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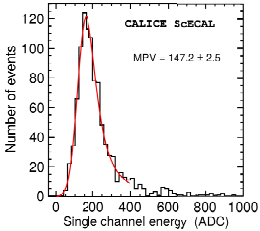
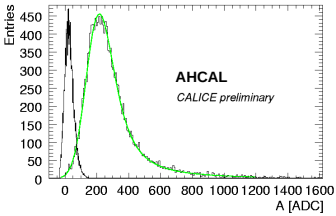
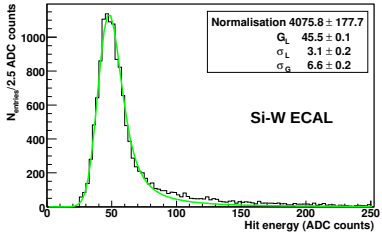
5.8 λ_I
320 channels

MIP Calibration

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







- 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

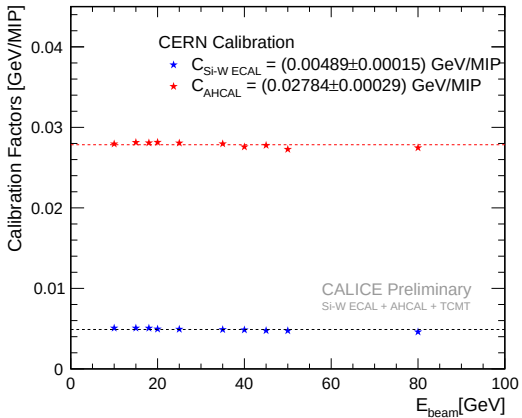
$$E_{\text{reco}}^{\text{event}} = C_{\text{ECAL}} \cdot \left(\sum_{j}^{\text{hits}} E_j^{\text{ECAL}}[\text{MIP}] c_t \right) + C_{\text{AHCAL}} \cdot \left(\sum_{j}^{\text{hits}} E_j^{\text{AHCAL}}[\text{MIP}] + \sum_{j}^{\text{hits}} E_j^{\text{TCMT}}[\text{MIP}] c_t \right)$$

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

1. Calibration factors for each beam energy:

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

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.

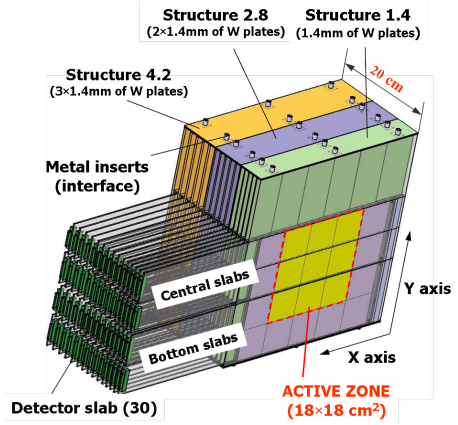
Each hit is weighted by the amount of absorber material in the respective layer.

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

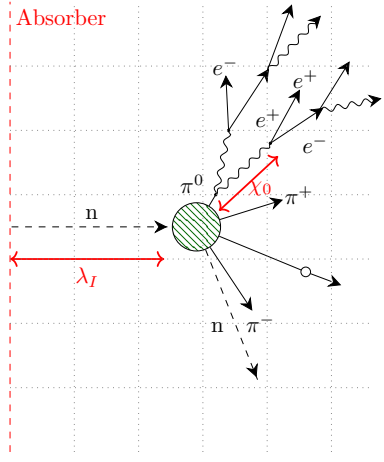
- Non-compensating calorimeters.
- Mean deposition of electrons higher than hadrons: $\frac{e}{h} > 1$.
- Fluctuation of EM fraction reduce energy resolution for hadrons.

Software Compensation:

- Different local energy density of electromagnetic and hadronic sub-showers.
- Weight each shower-hit in the reconstruction, according to the local energy density.
- Expected:

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

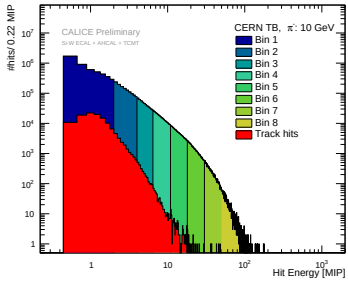
↪ higher density hits (mostly EM) → weights<1

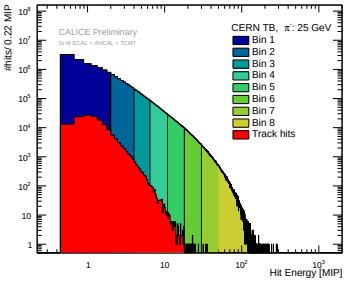


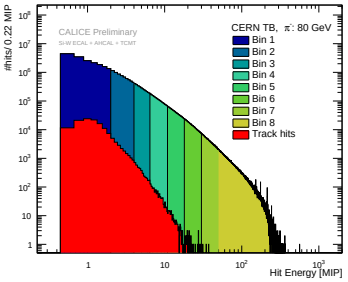
Software Compensation Energy Reconstruction

- Different local energy density of electromagnetic and hadronic sub-showers.
- Weight each shower-hit in the reconstruction, according to the local density.

- Hit energy in 8 bins→ weight for each bin.
- Primary track via standard reconstruction.





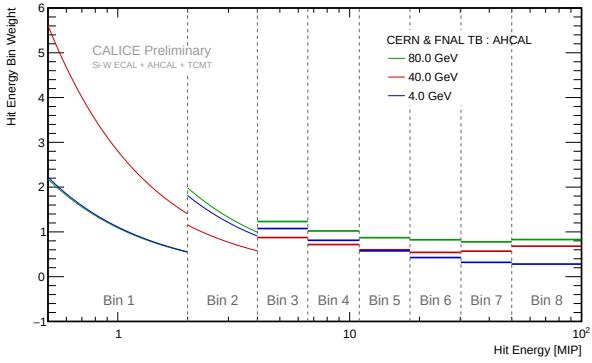


Software Compensation Weights

- $\omega_j(E)$: Bin weights are parametrised with beam energy.
- 2nd order polynomials.
- 3 parameters for each bin: a_j, b_j, c_j.

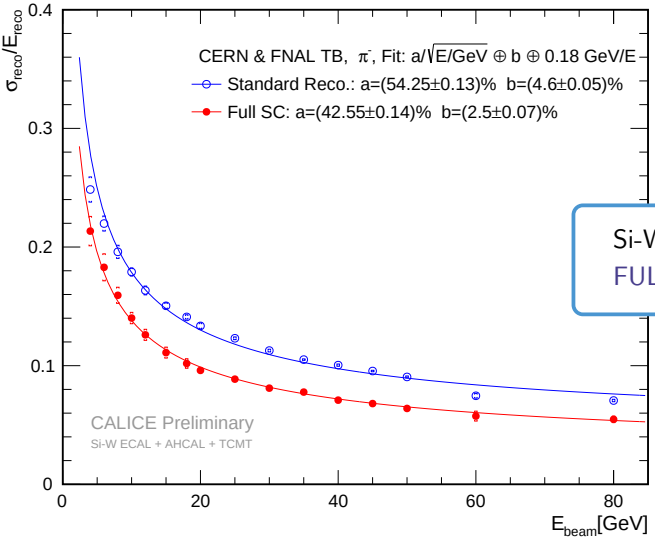
$E = E_{\text{beam}}$ in weights optimization.
$E = E_{\text{reco}}$ in SC energy reconstruction.

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



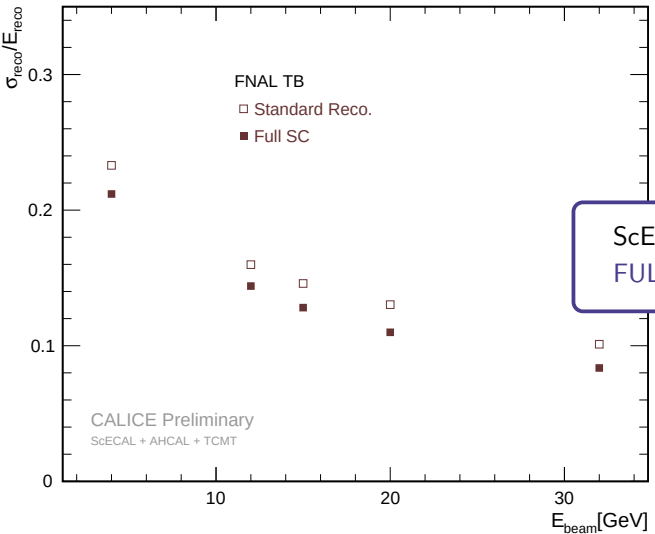
- Binary reconstruction in bins 1-2 to suppress Landau fluctuations.

Energy Resolution Results



Si-W ECAL + AHCAL + TCMT
FULL SC up to 30% improvement.

Energy Resolution Results

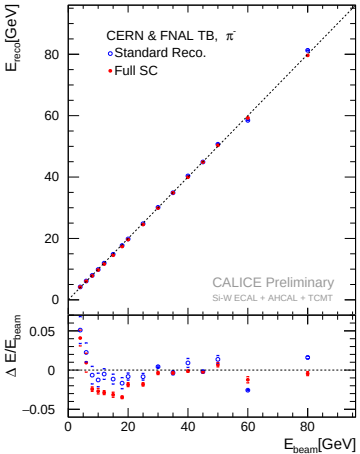


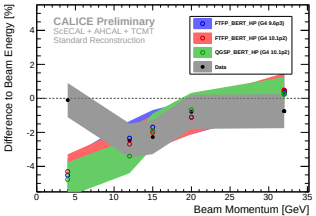
ScECAL + AHCAL + TCMT
FULL SC up to 20% improvement.

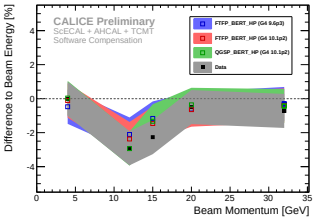
Linearity Results

Si-W ECAL + AHCAL + TCMT
Deviations from E_{beam} < 5%.

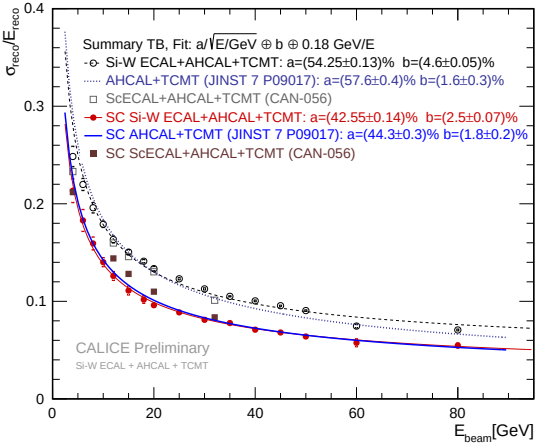
ScECAL + AHCAL + TCMT
Deviations from E_{beam} < 4%.







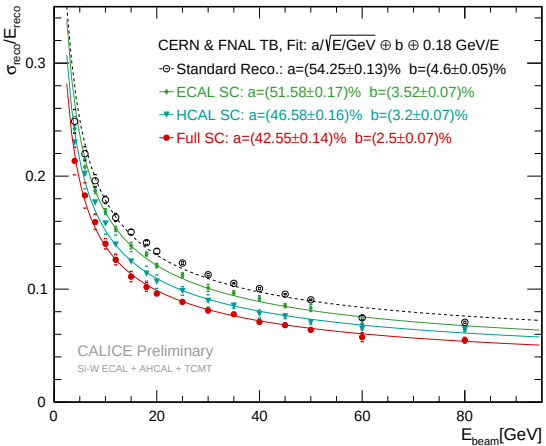
Results Summary



- Comparison with reference analysis AHCAL+TCMT : JINST 7 P09017
  - ▷ Shower starts: first 5 layers of AHCAL.
  - ▷ SC applied to AHCAL+TCMT.
- Analysis with ECAL data shows similar performance as AHCAL+TCMT analysis despite the:
  - ▷ different absorber material (W, Fe)
  - ▷ different structure (Si-W ECAL)

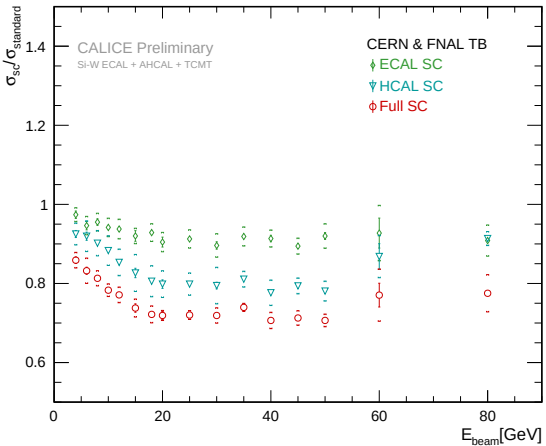
Applying SC to Different Detectors

ECAL SC in Si-W ECAL (24 parameters)
HCAL SC in AHCAL and TCMT (27 parameters)
FULL SC in all 3 detectors (51 parameters)

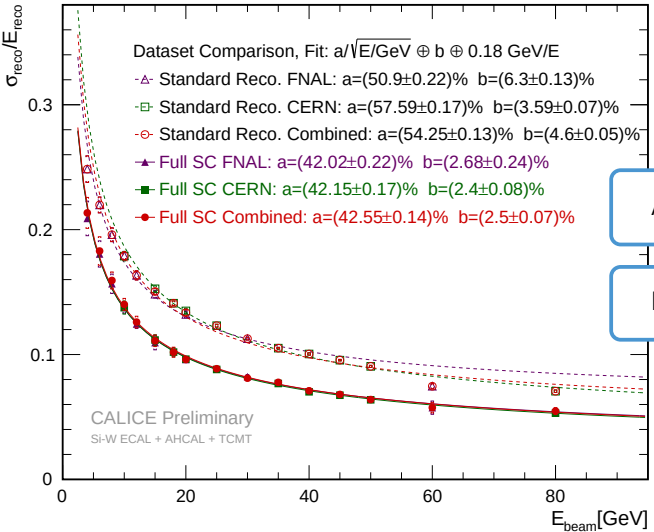


Applying SC to Different Detectors

ECAL SC in Si-W ECAL (24 parameters) → up to 8% improvement
HCAL SC in AHCAL and TCMT (27 parameters) → up to 23% improvement
FULL SC in all 3 detectors (51 parameters) → up to 30% improvement



Reconstruction of Different Datasets



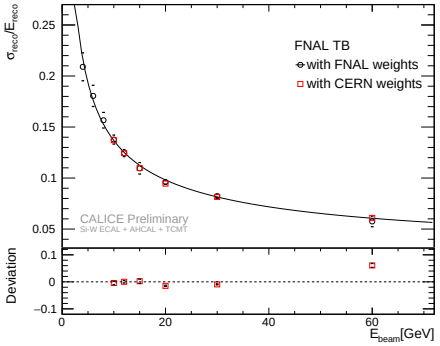
Agreement within 2.5% for datasets

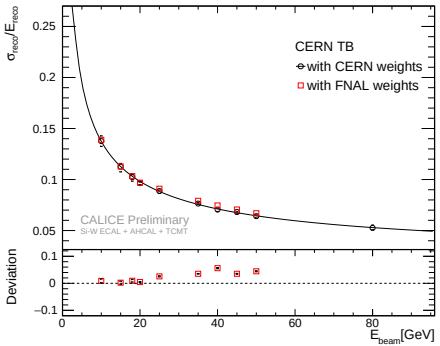
Detector performance is consistent.

Application of Weights to Different Beam Periods

Systematic test of the robustness of the SC method:

- 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%)

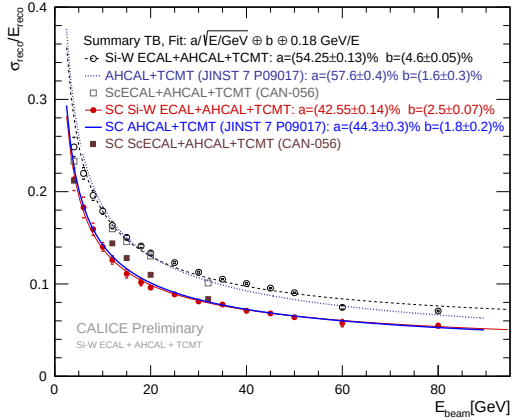
Deviation with energy dependence
up to ~6%

Summary

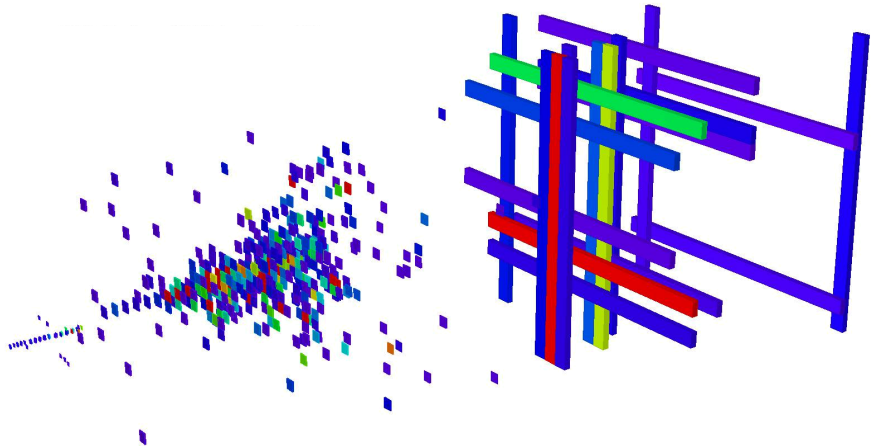
- Two analyses of CALICE high granularity combined full calorimeter systems
  - Si-W ECAL + AHCAL + TCMT : CALICE Analysis Note 058
  - ScECAL + AHCAL + TCMT : CALICE Analysis Note 056

- Applying SC to different detectors improves the energy resolution up to:
  - Full SC - 30%/20%
  - HCAL SC - 23%
  - ECAL SC - 8%

- Test of the robustness of the SC method:
  - Deviation$\leqslant$6%.



Thank you for your attention ☺



BACKUP

Software Compensation Weights

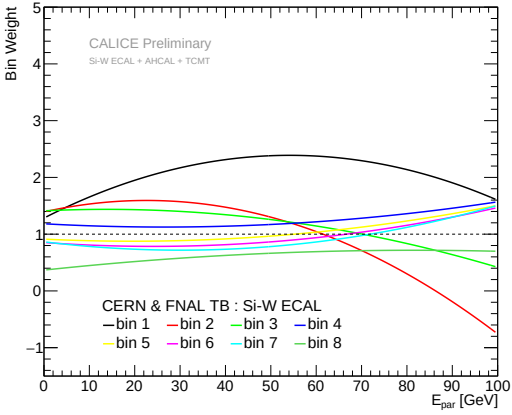
Bin weights parametrised with beam energy:
2nd order Chebyshev polynominal

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

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

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

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



SC Schemes

FULL SC in all 3 detectors (51 parameters):

$$E^{\text{event}}_{\text{Full SC}} = C_{\text{Si-W ECAL}} \cdot \left(\sum_{i}^{\text{bins}} \alpha_i(E) \cdot E_i^{\text{Si-W ECAL}} + E^{\text{Si-W ECAL}}_{\text{track}} \right) + C_{\text{AHCAL}} \cdot \left(\sum_{i}^{\text{bins}} \beta_i(E) \cdot E_i^{\text{AHCAL}} + E^{\text{AHCAL}}_{\text{track}} + \gamma(E) \cdot E^{\text{TCMT}}_{\text{sum}} \right) \quad (2$$

HCAL SC in AHCAL and TCMT (27 parameters):

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

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

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

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)

$\Longrightarrow$ set constant energy contributions from these bins

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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).