Energy Reconstruction with Software Compensation Techniques in Highly Granular Calorimeters

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MPP PhD Recruiting Workshop

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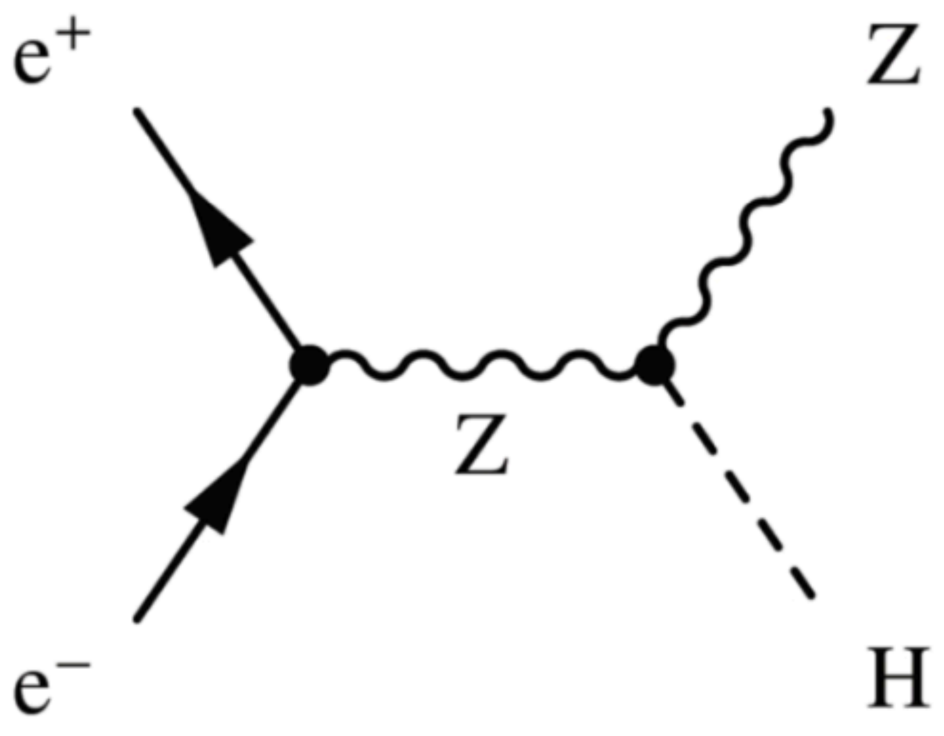
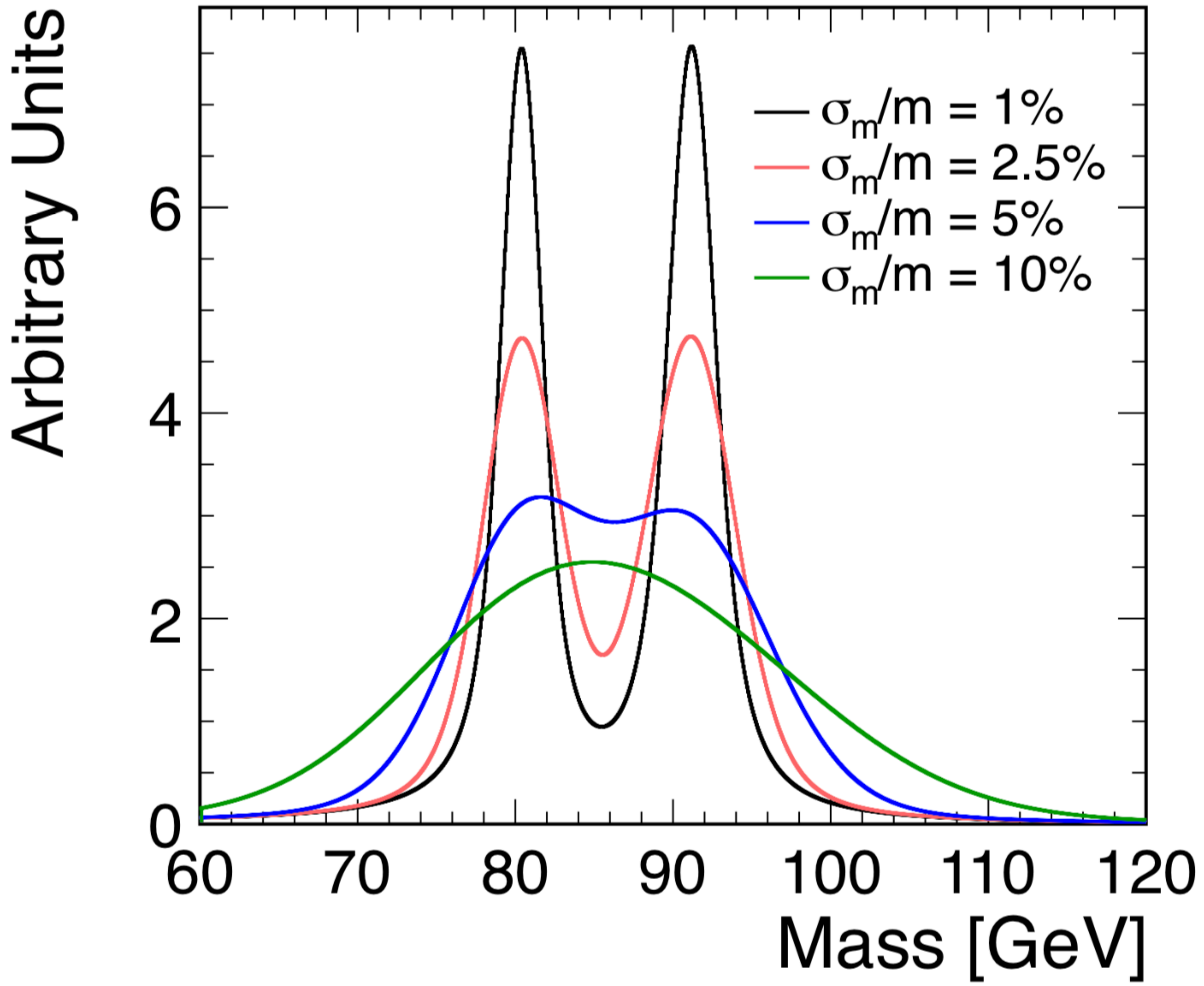
Motivation

- Physics program at future e^+e^- collider experiments (ILC, CLIC) includes:
  - Higgs precision measurement
  - Search for physics beyond the SM
  - Electroweak precision measurement

→**Requires precise reconstruction of all final states**

→**In turn needs jet energy resolution of 3 - 4%**





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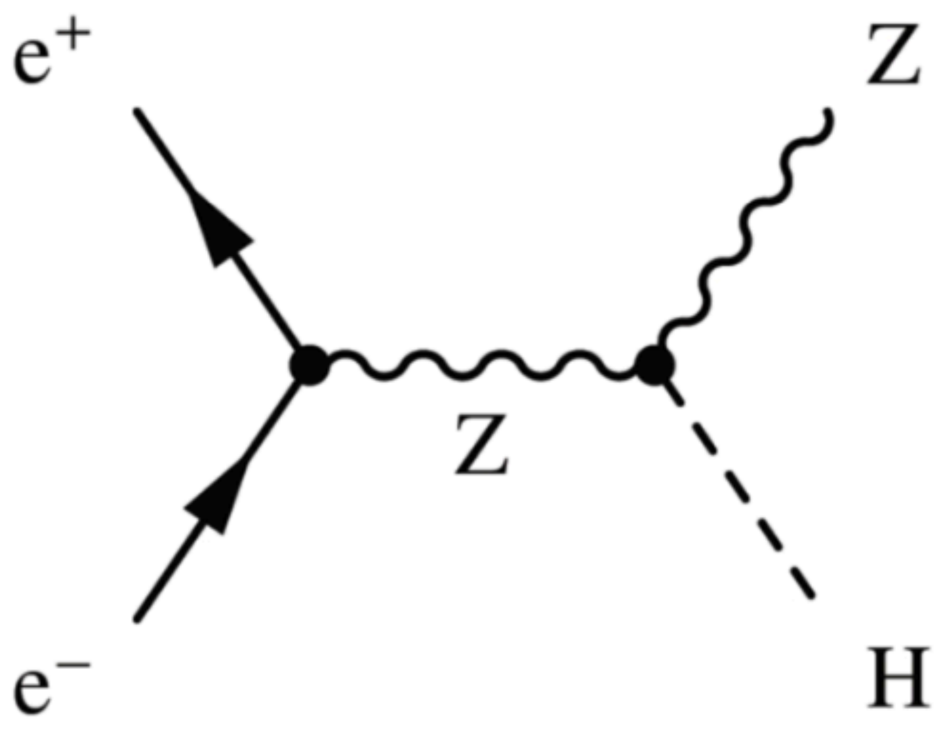
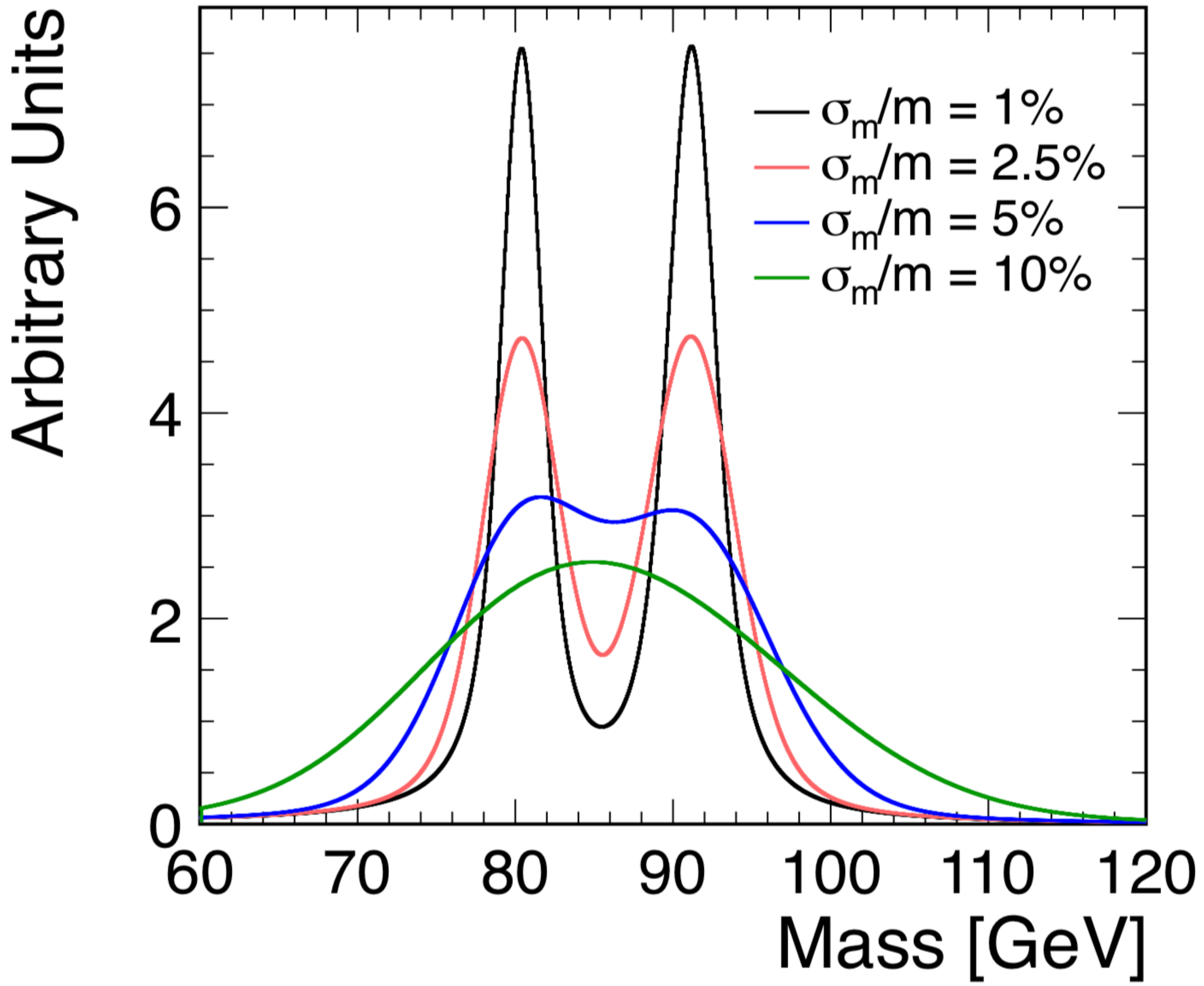




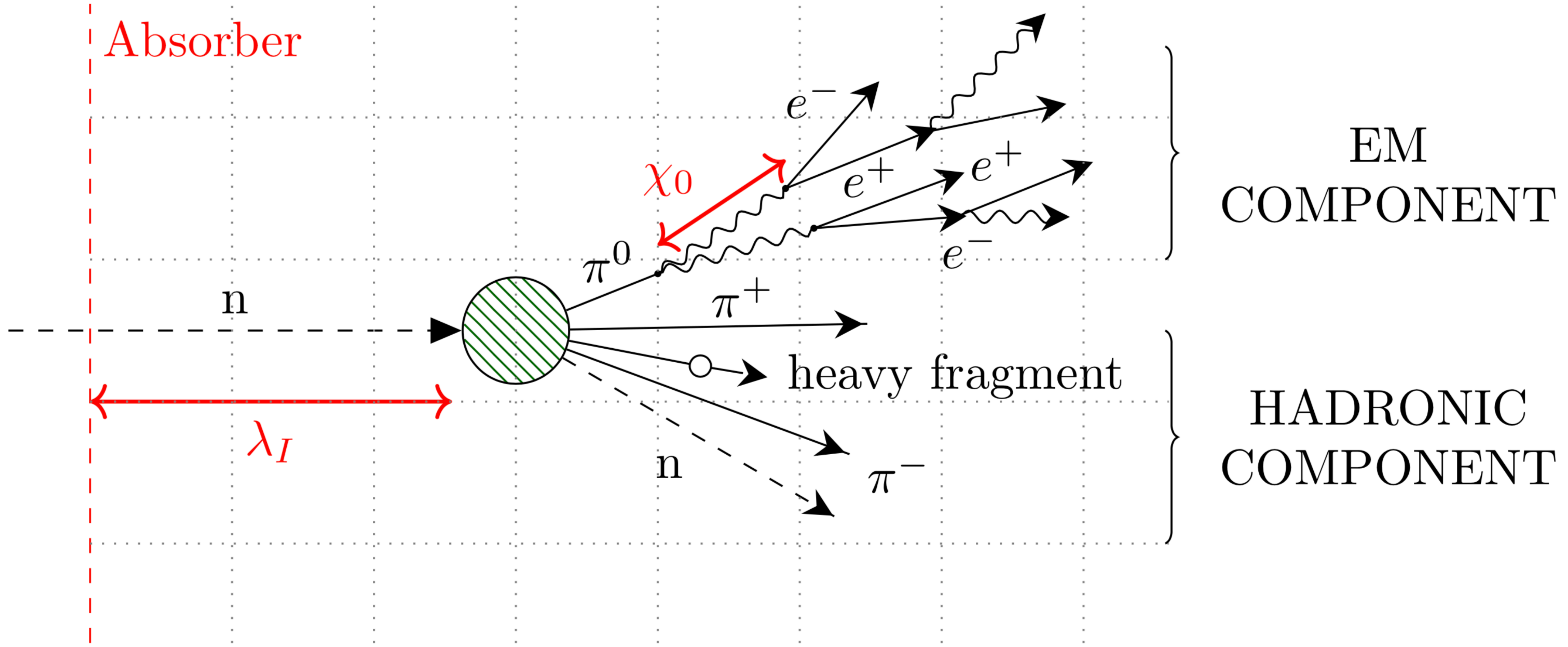
Requires capable detector system and advanced reconstruction methods

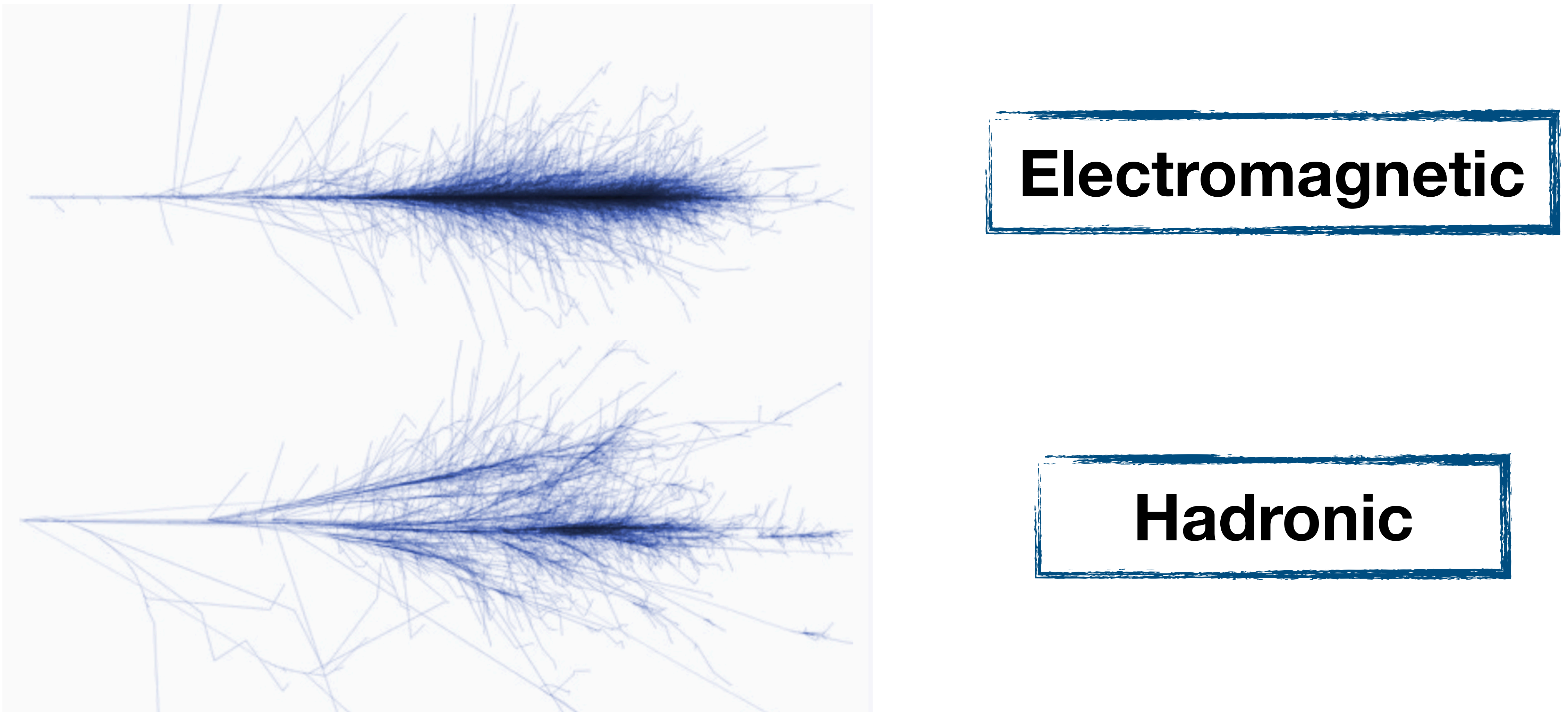
Particle Showers

- Particle shower consists of EM and hadronic component
- EM showers are denser than hadronic ones
- Fluctuations of energy deposited in electromagnetic component
- Hadronic shower has invisible energy
- Different response to hadronic and electromagnetic component of shower depending on the calorimeter

→ **Results in deterioration of energy resolution**

→ **Can be fixed hardware or software wise**





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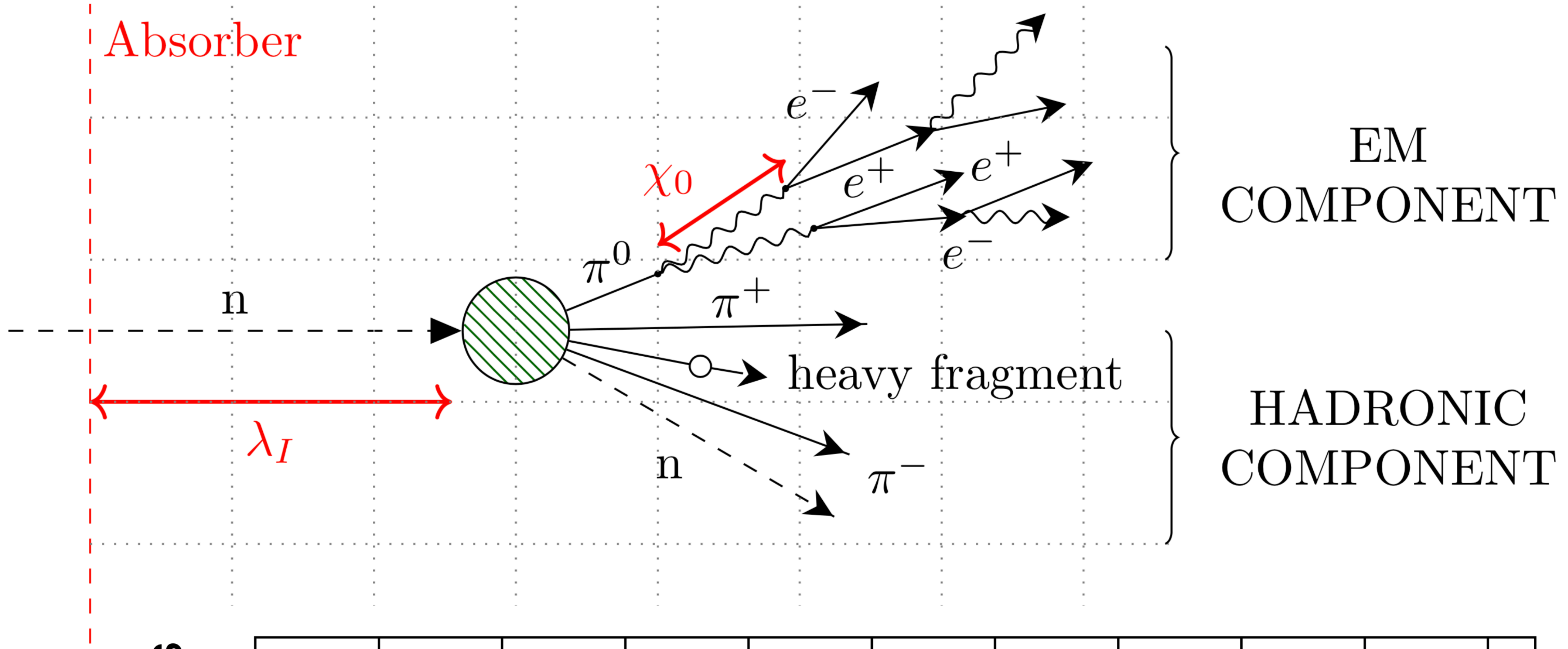

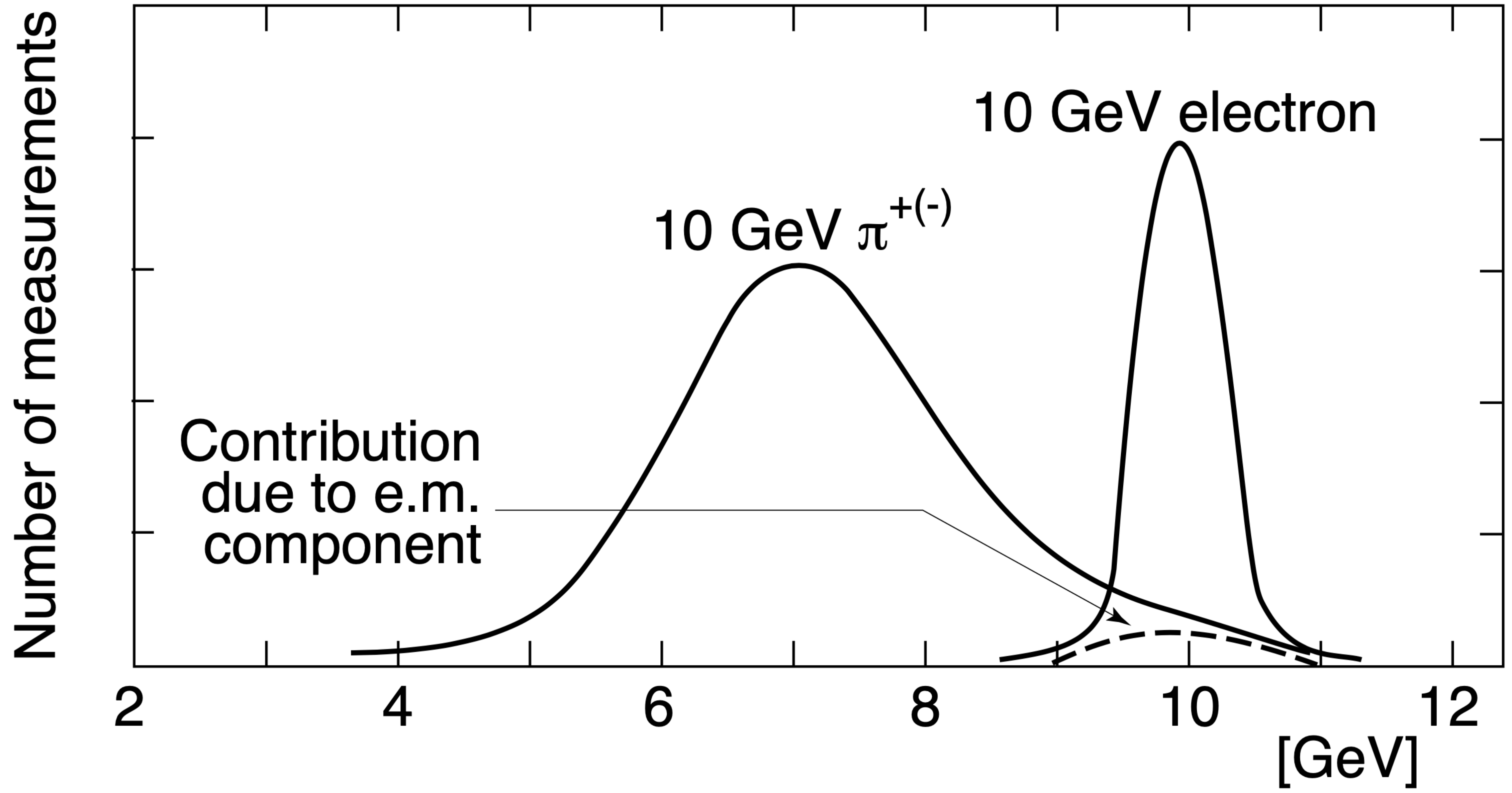

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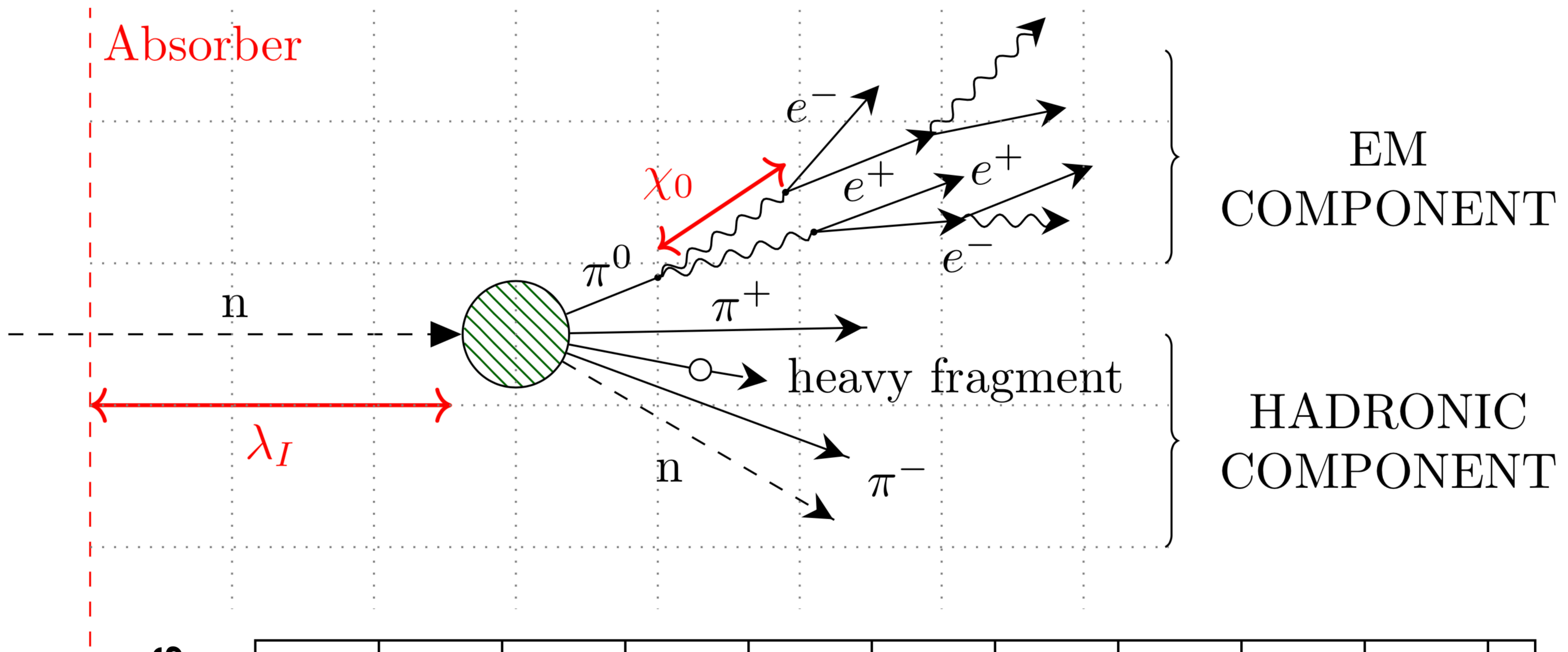
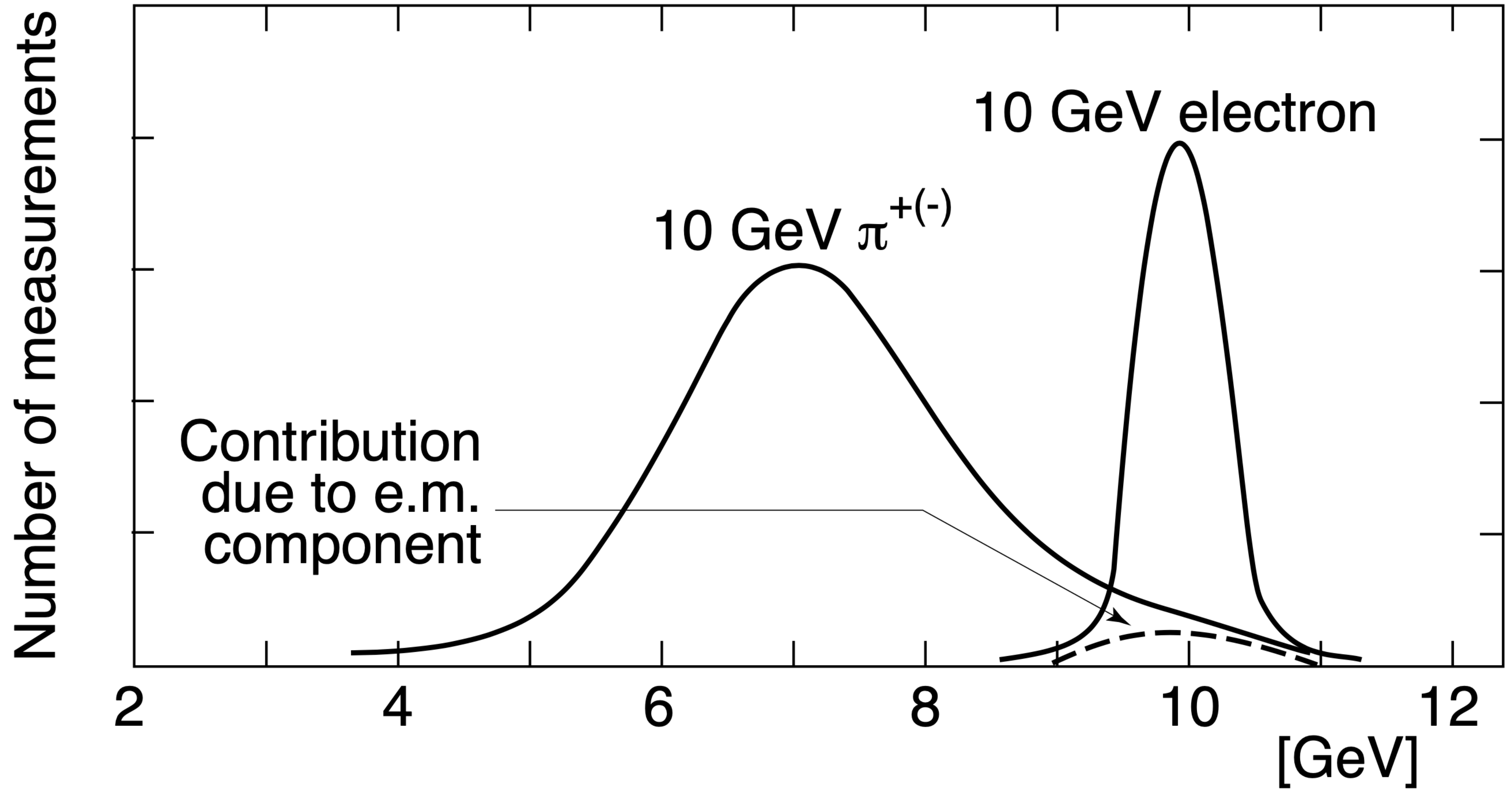
Recover energy resolution with local software compensation





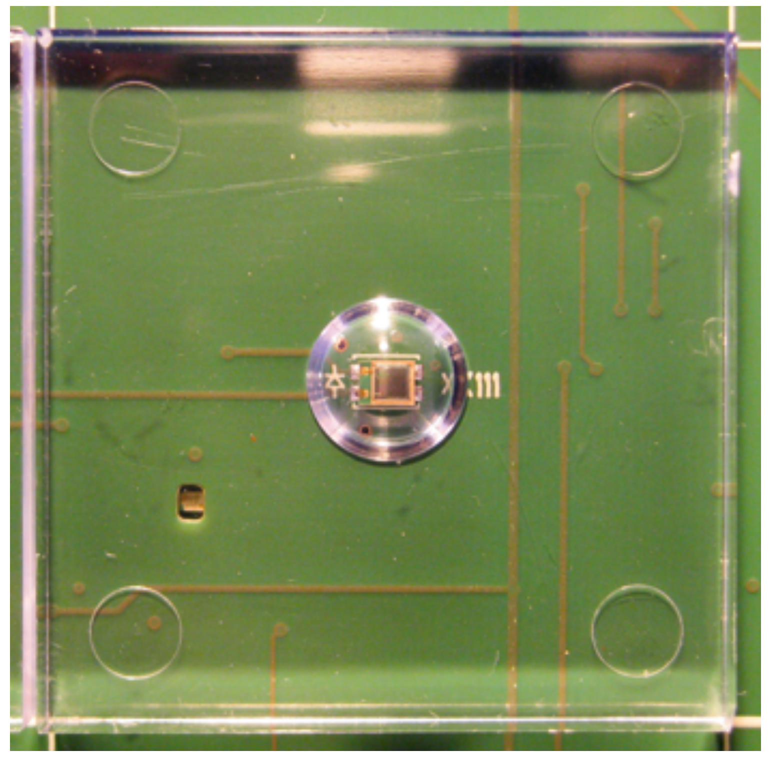
CALICE Calorimeter

AHCAL:

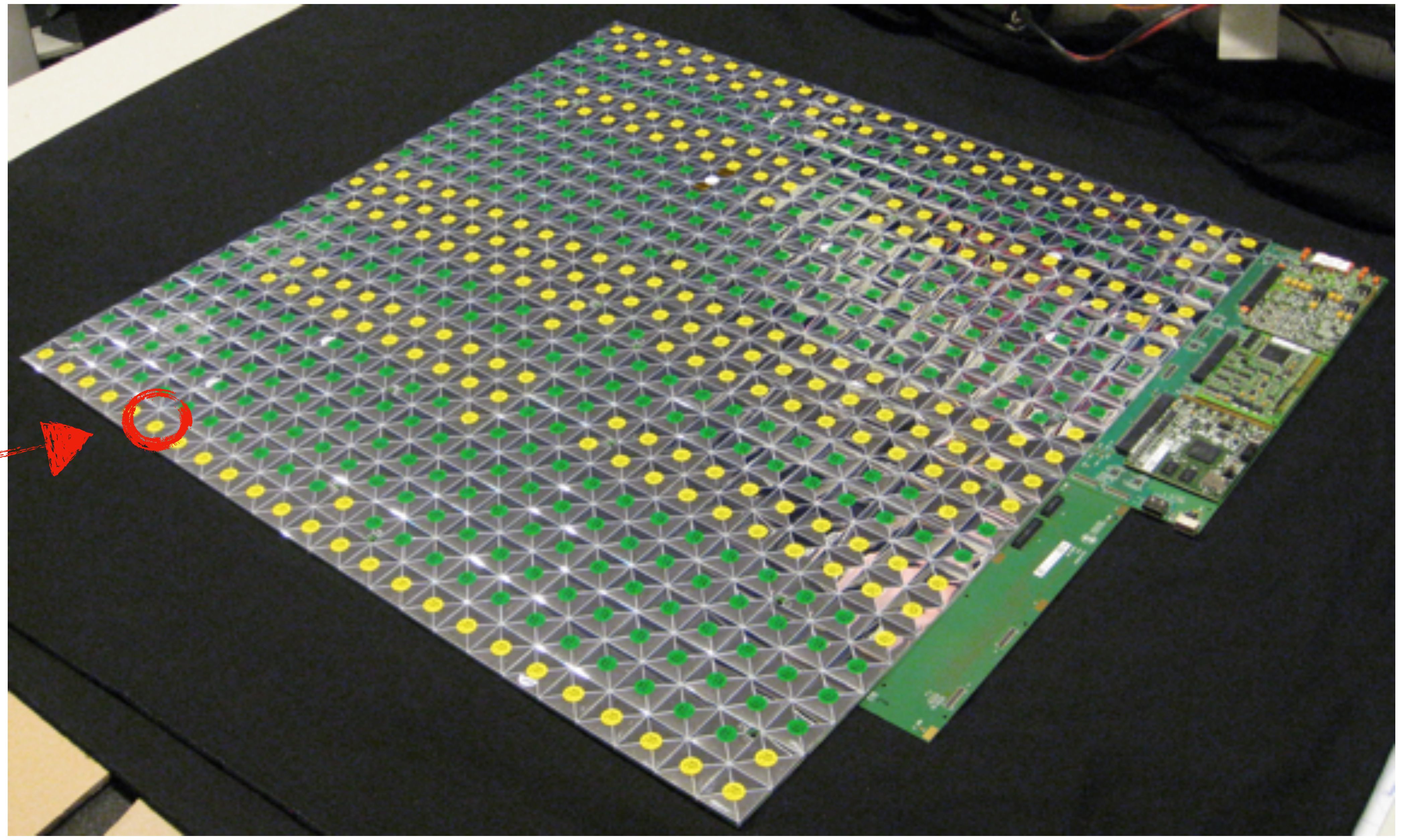
- Sampling calorimeter
- Active layer consists of:
  - Plastic scintillator
  - SiPM
- High spatial resolution enables new reconstruction techniques

3 cm

3 cm



Single cell



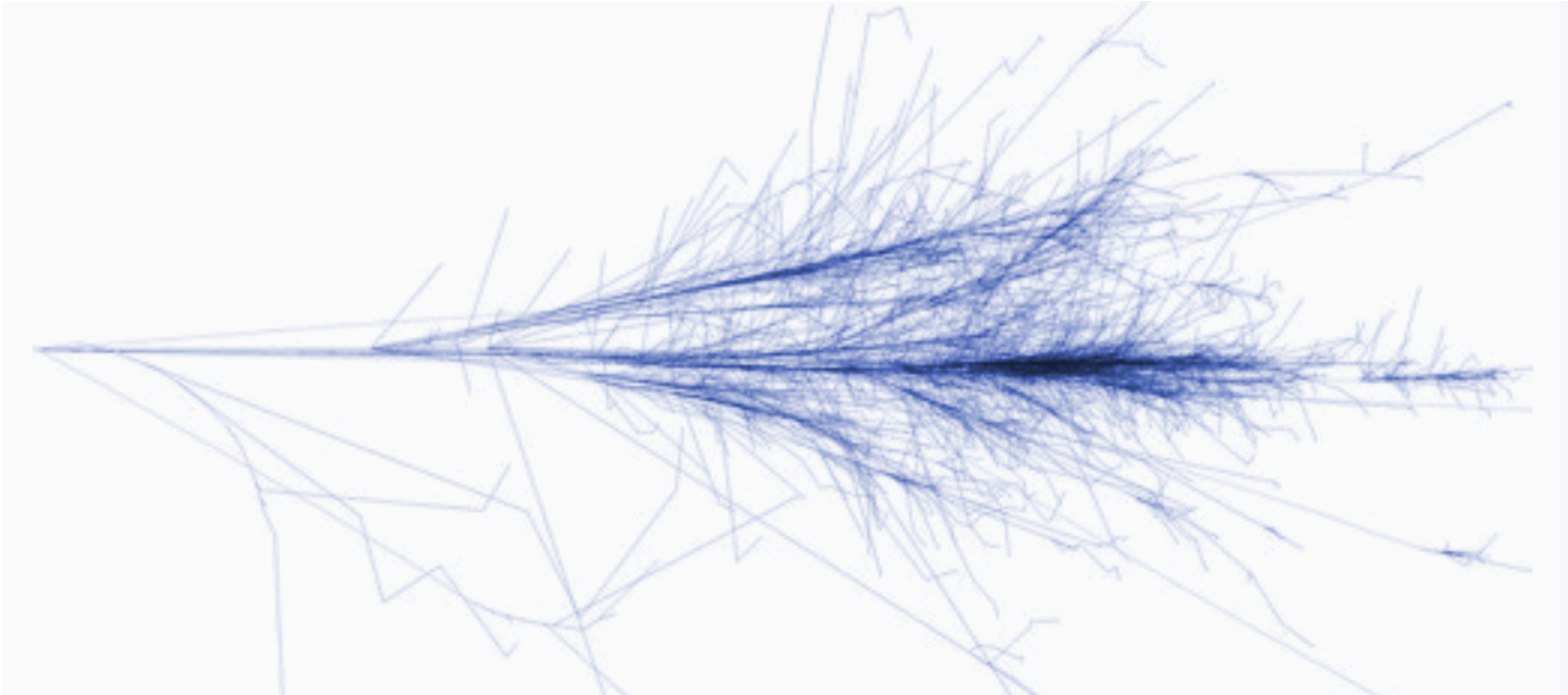
Assembled layer

Local Software Compensation

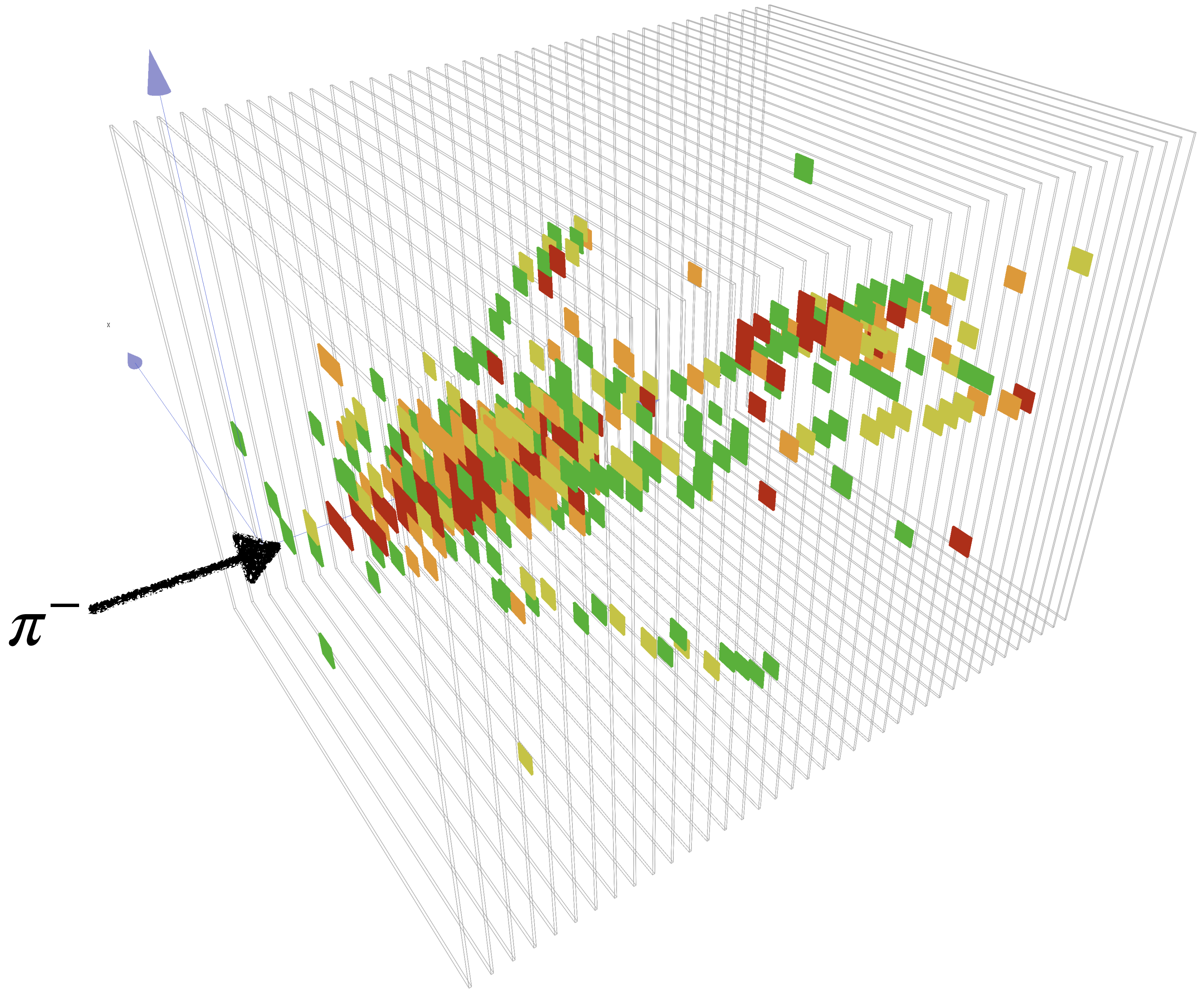
Local software compensation idea:

- Exploit high granularity of calorimeter
- Apply different weights to hits
- Correct difference in response
- Improve energy resolution

Simulation



Data



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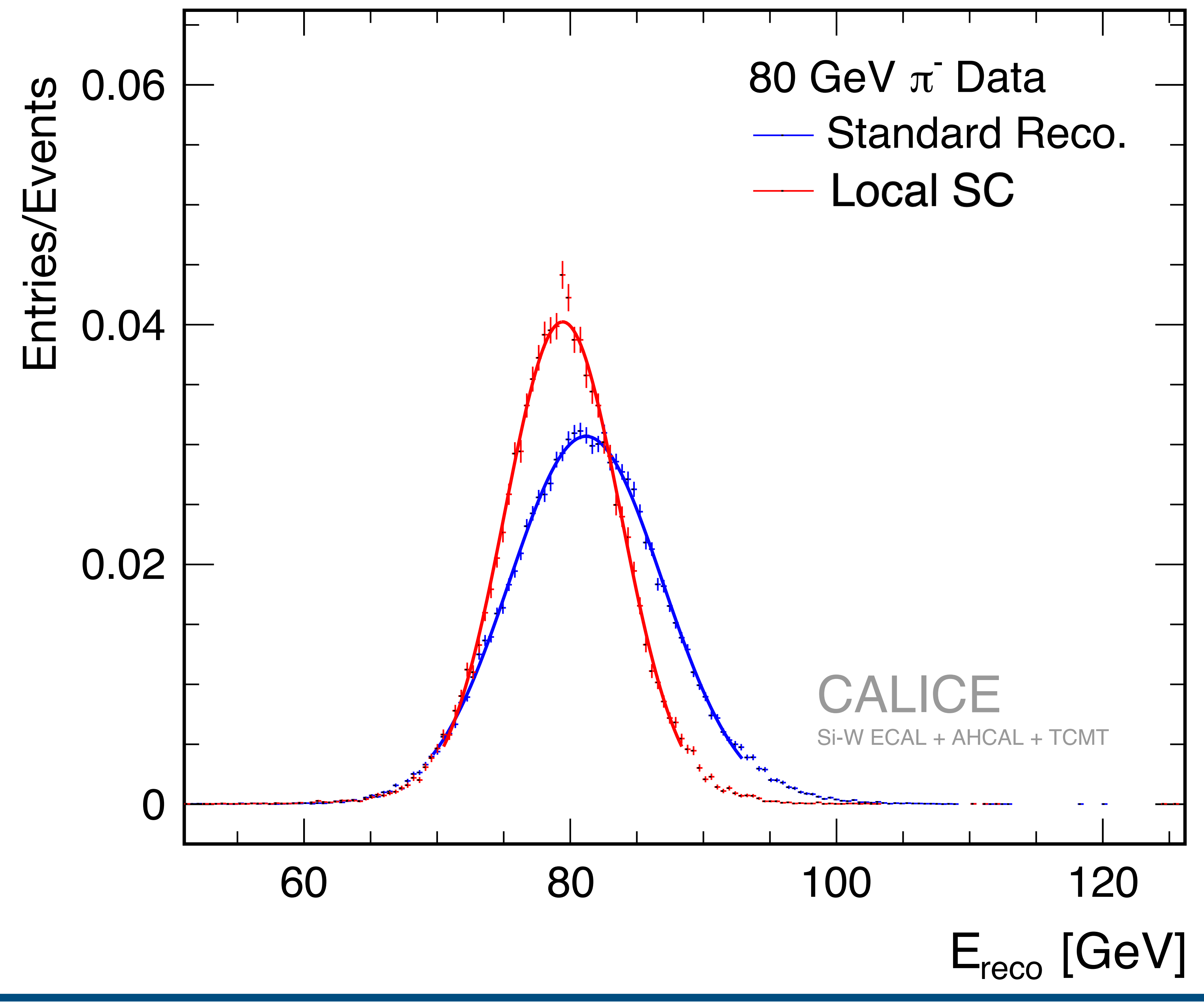

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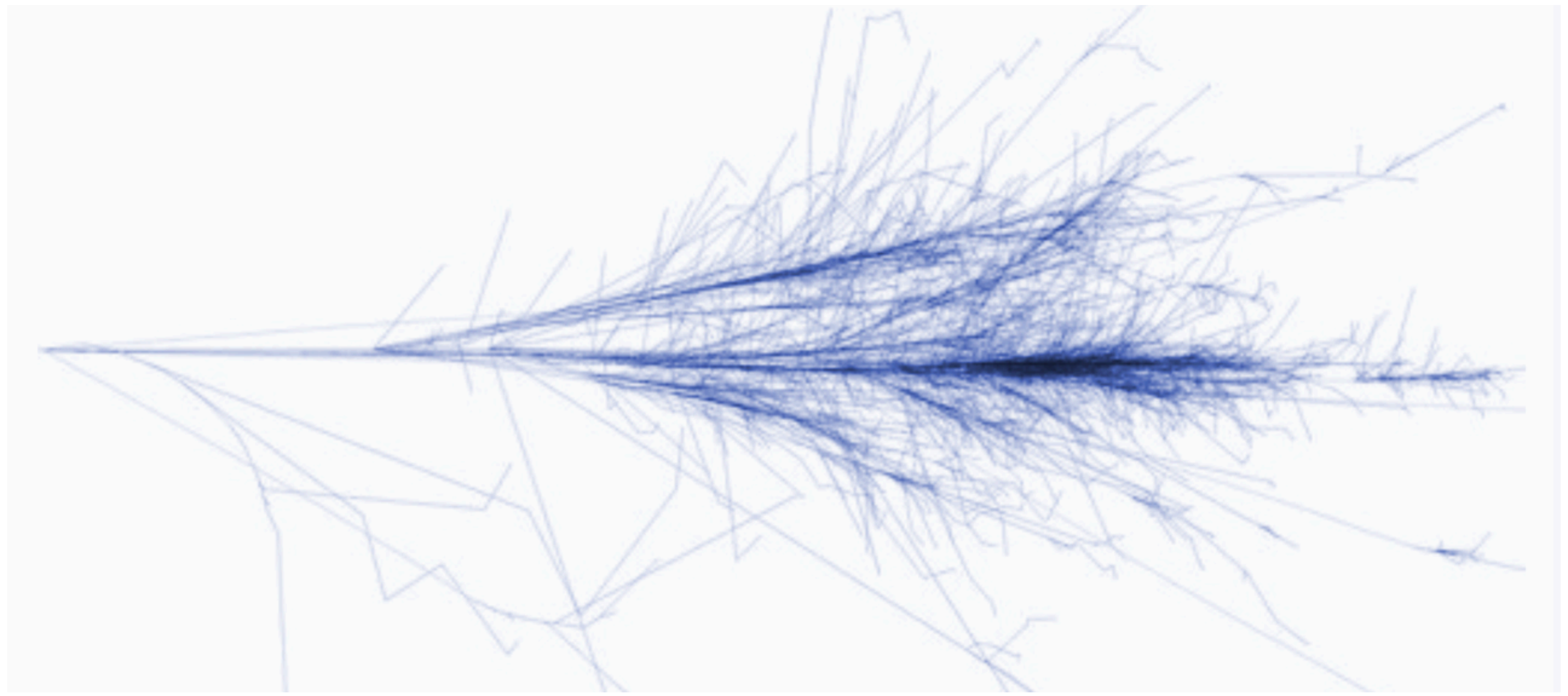
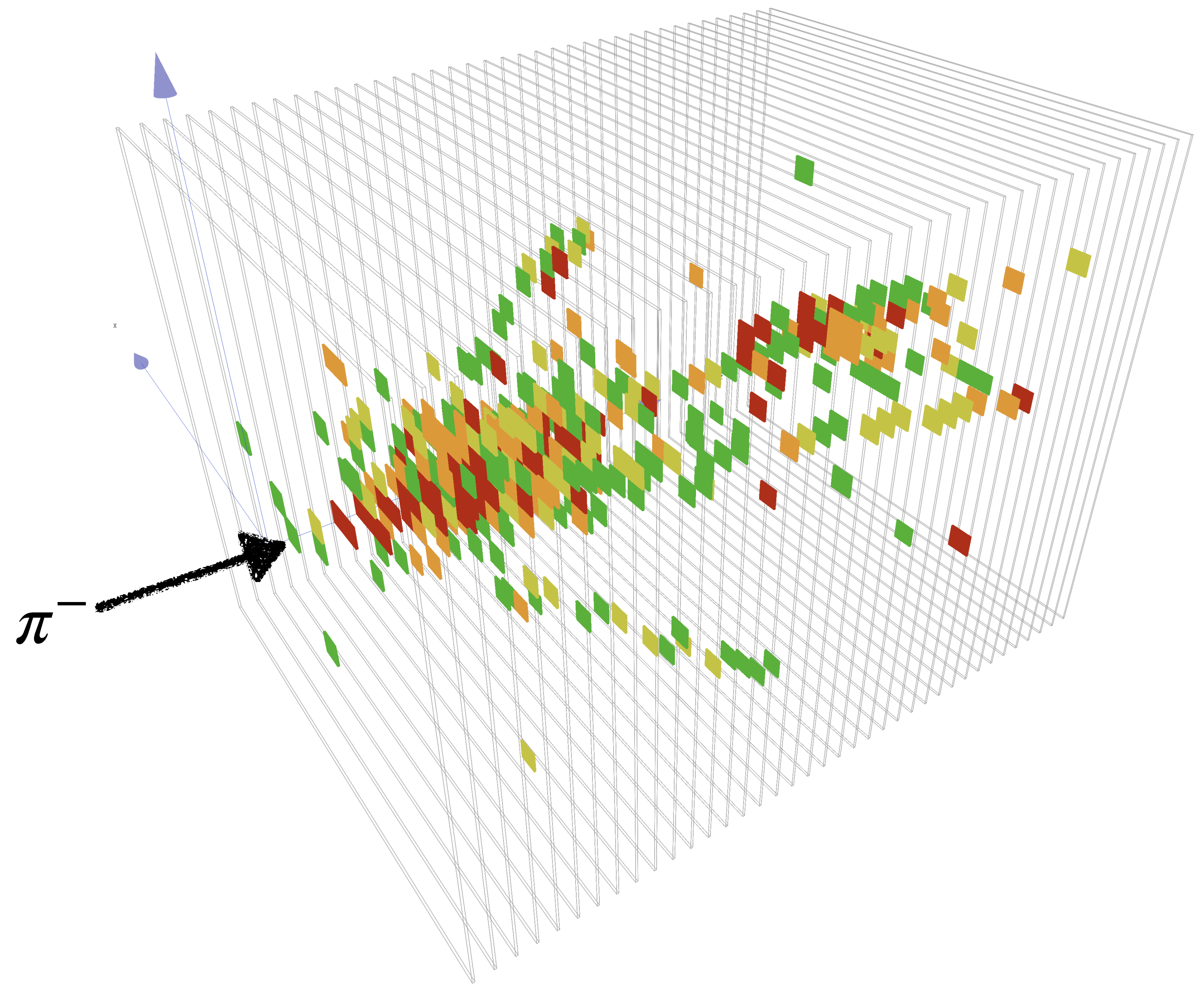
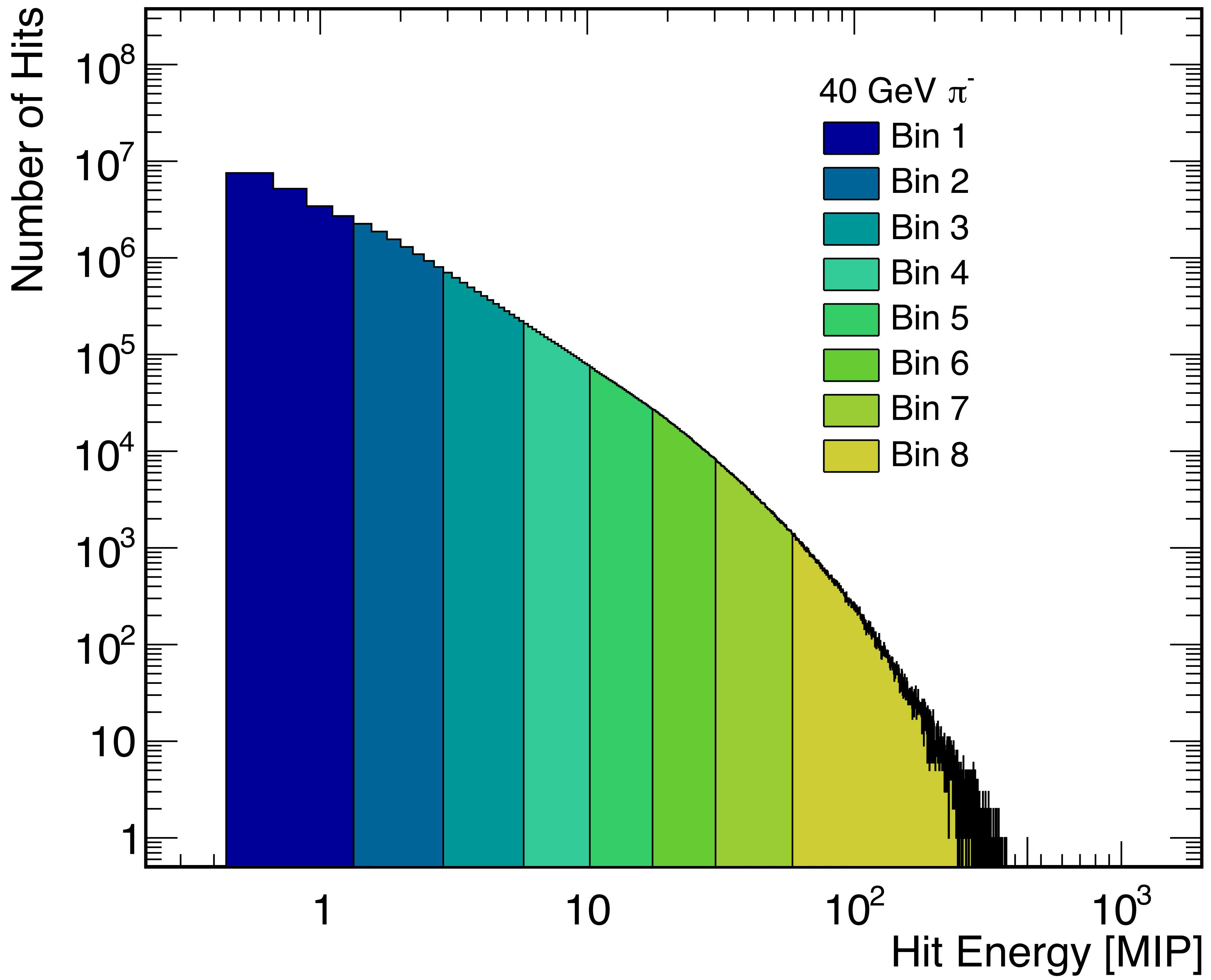


Data



Local Software Compensation



- Divide hit energy spectrum into bins with same amount of energy
- Apply weight for each bin for each event

Reconstructed energy for each event: $E_{SC}^{event} = C_{W-AHCAL} \sum_{i}^{bins} \omega_i(E) \cdot E_i$

Energy dependent weights : $\omega_i(E) = a_i + b_i \cdot \frac{E}{S} + c_i \cdot \left(2 \cdot \left(\frac{E}{S}\right)^2 + 1\right)$

Loss function in order to find optimal bin weights: $L = \sum_{events} \left(\frac{(E_{SC}^{event} - E_{beam}^{event})^2}{(55\,\%\sqrt{GeV})^2 \cdot E_{beam}^{event} \cdot N_{beam}^{event}} \right) + \alpha \cdot \sum_{p} \xi_p(E)$

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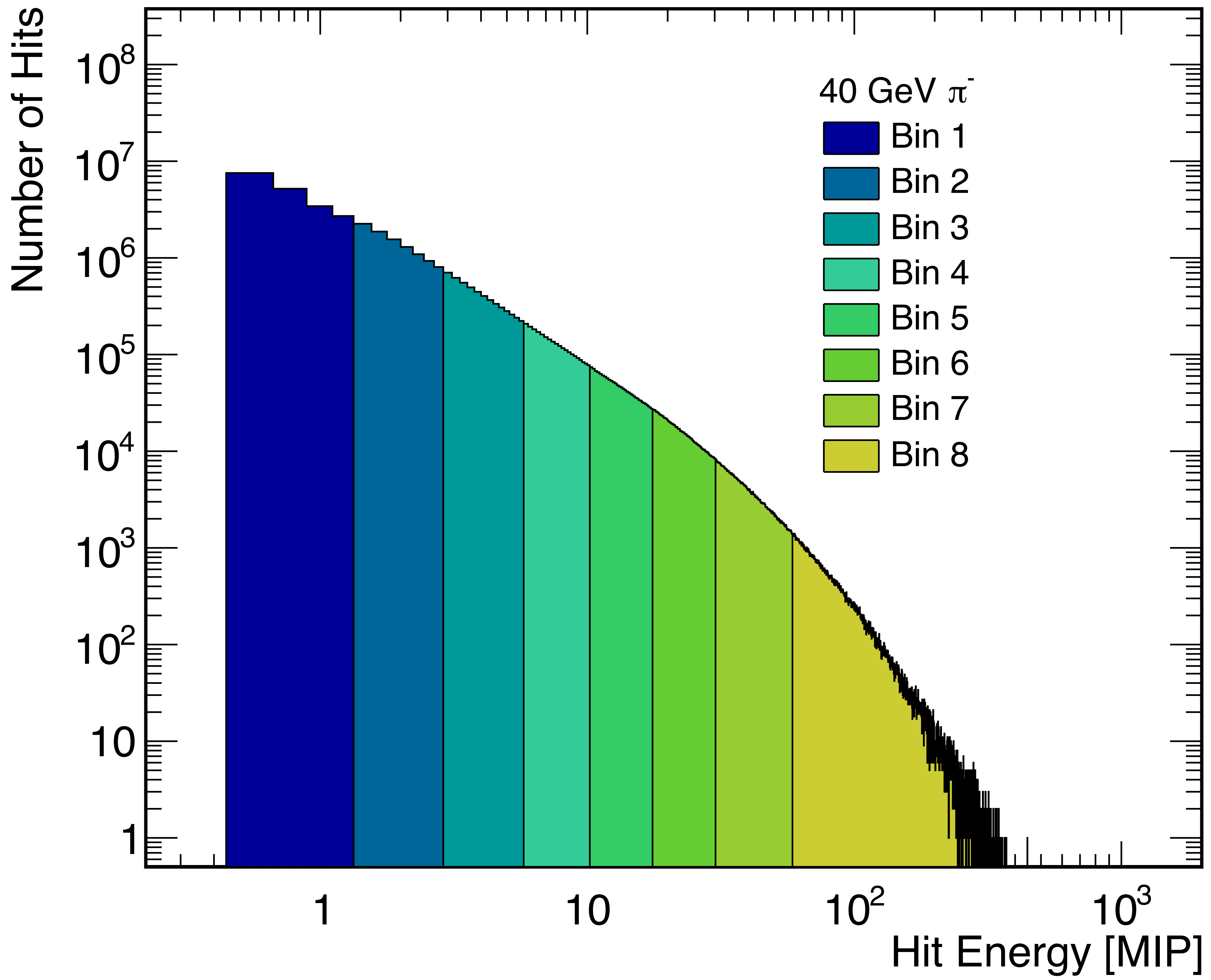

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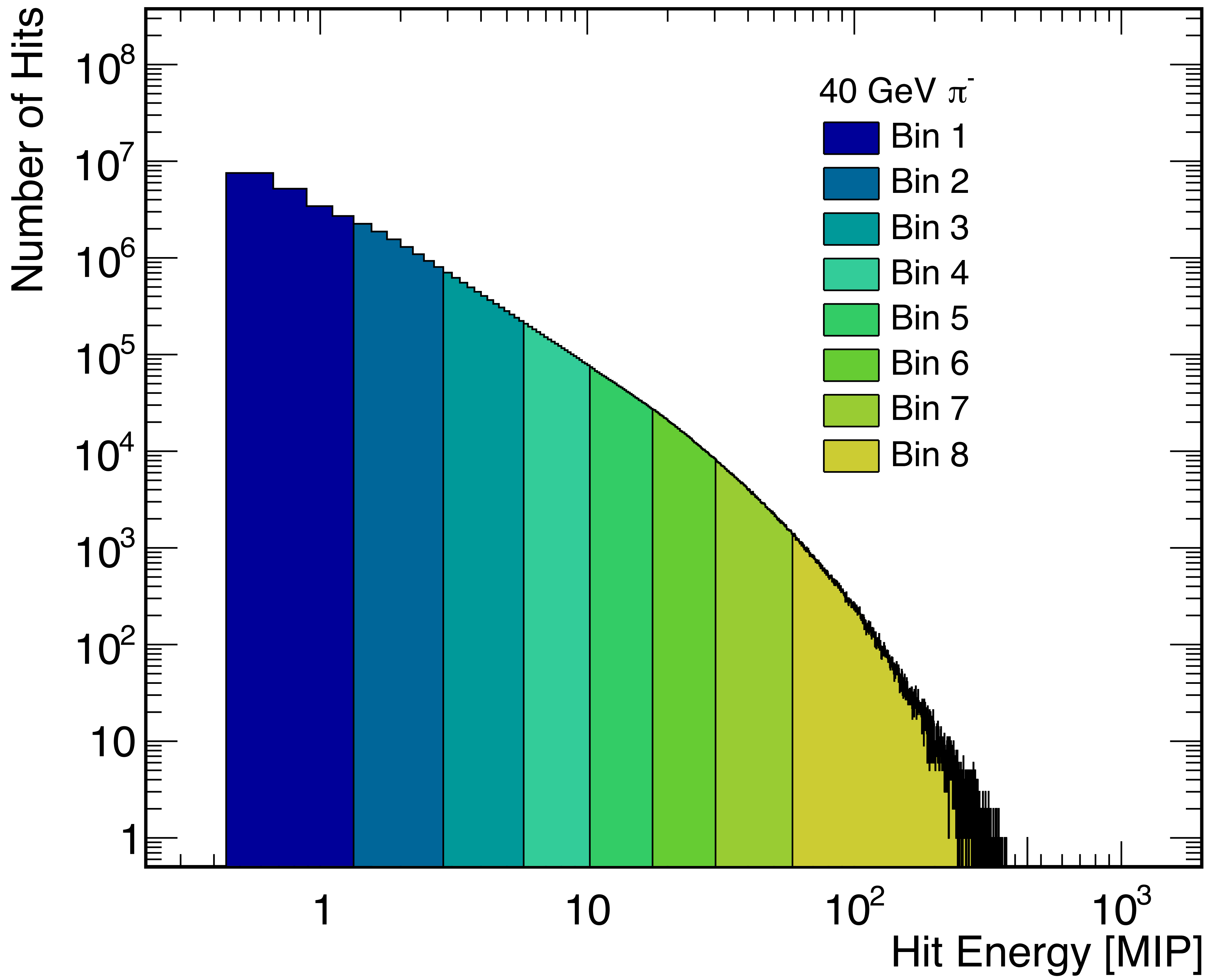

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χ^2

Penalty Term

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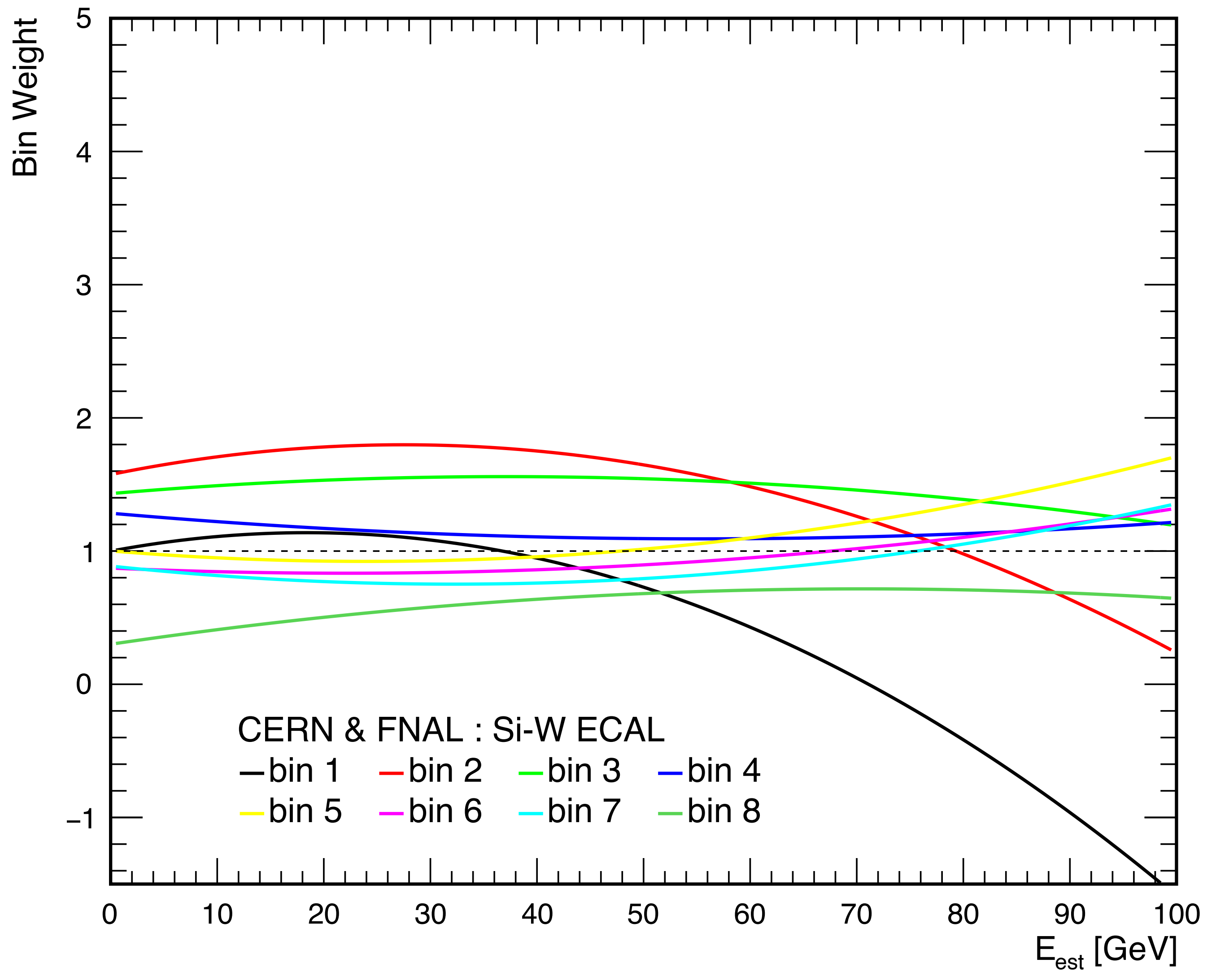
Problem: High local gradients of weight function lead to unphysical behavior

Weight function: $\omega_i(\mathrm{E}) = a_i + b_i \cdot \frac{\mathrm{E}}{S} + c_i \cdot \left(2 \cdot \left(\frac{\mathrm{E}}{S}\right)^2 + 1\right)$



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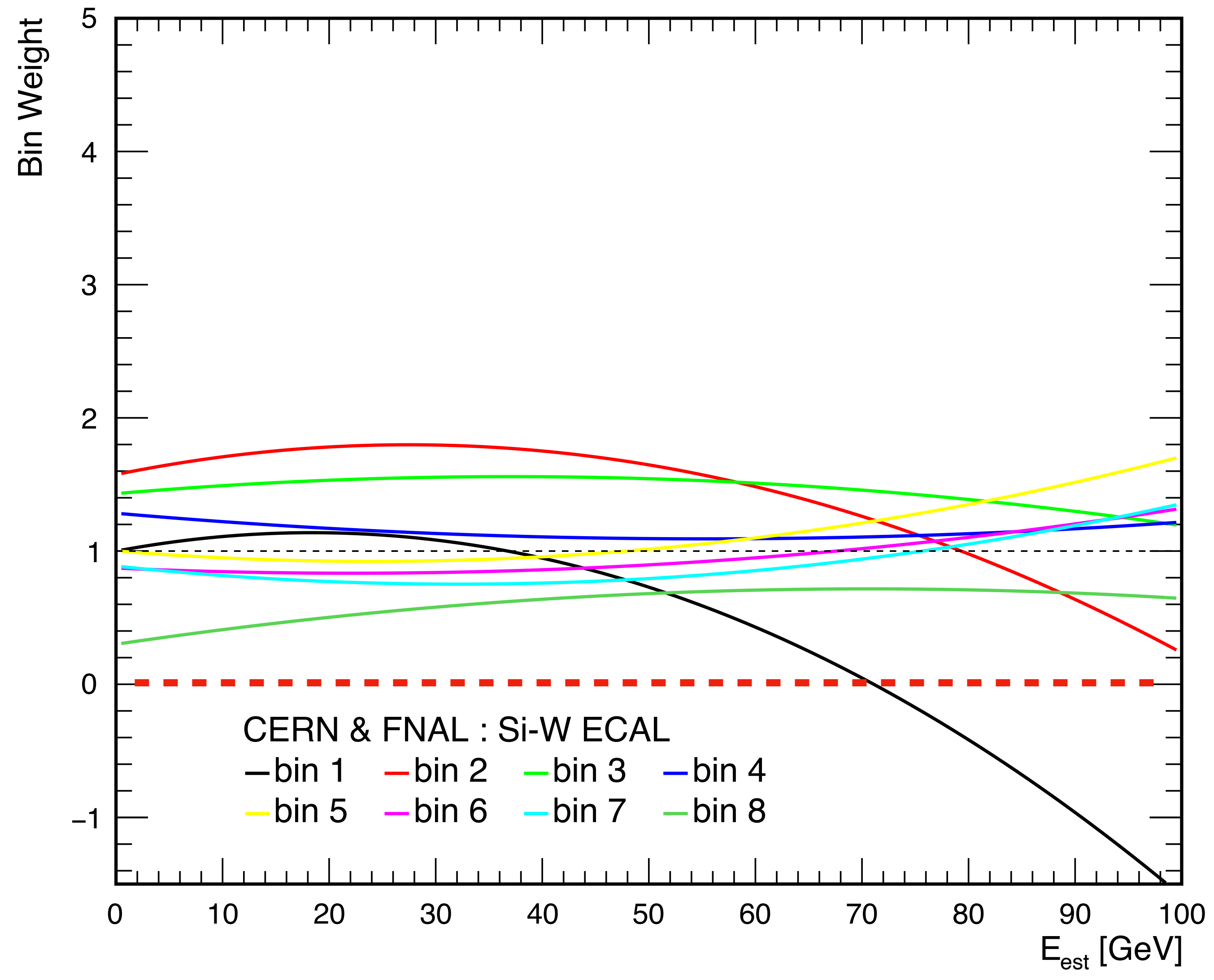

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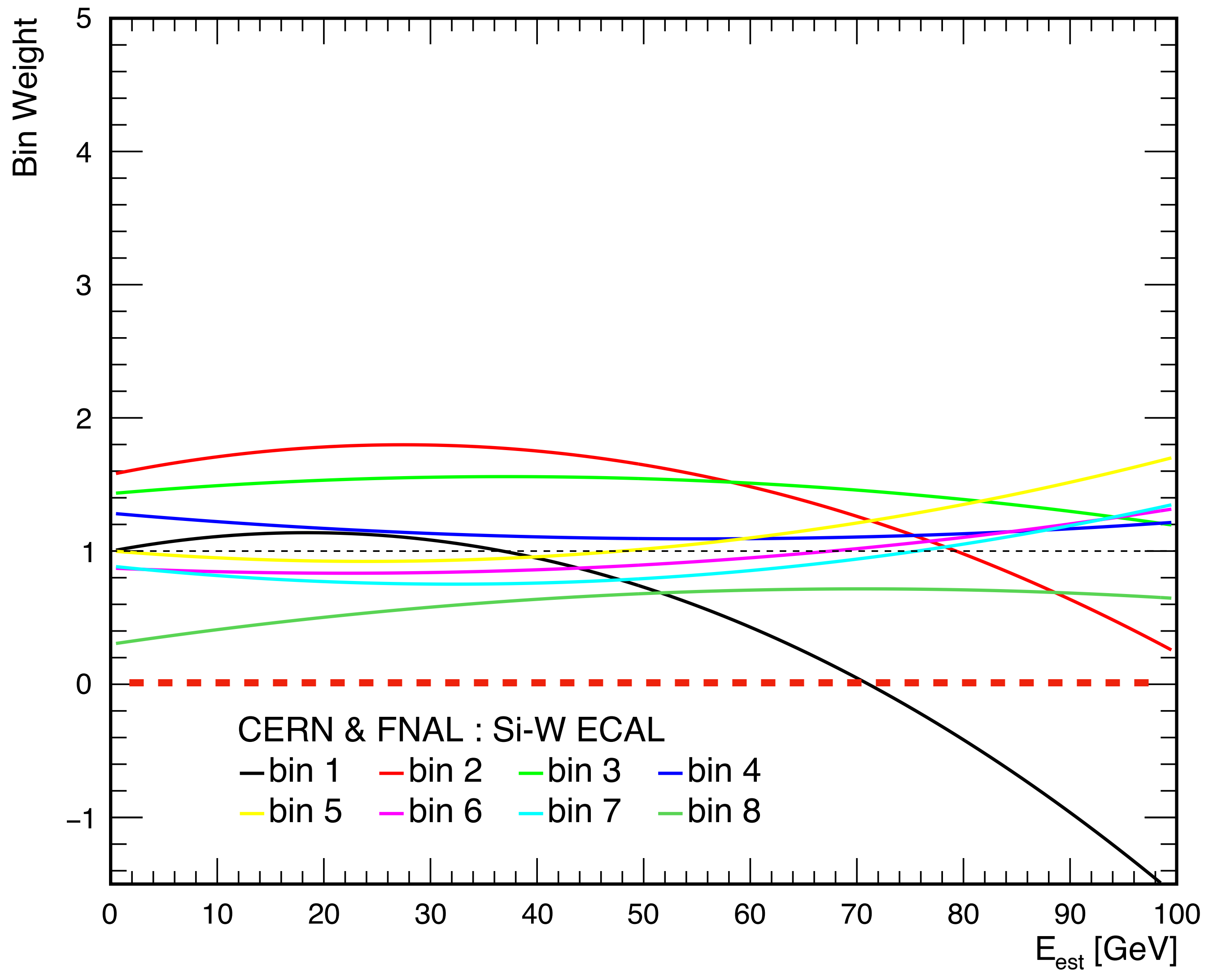

Solution: Enhance loss function by adding penalty term

Penalty term: $\xi(\mathrm{E}) = \sum_i \left(\frac{d}{d(E/S)}\omega_i(\mathrm{E})\right)^2$

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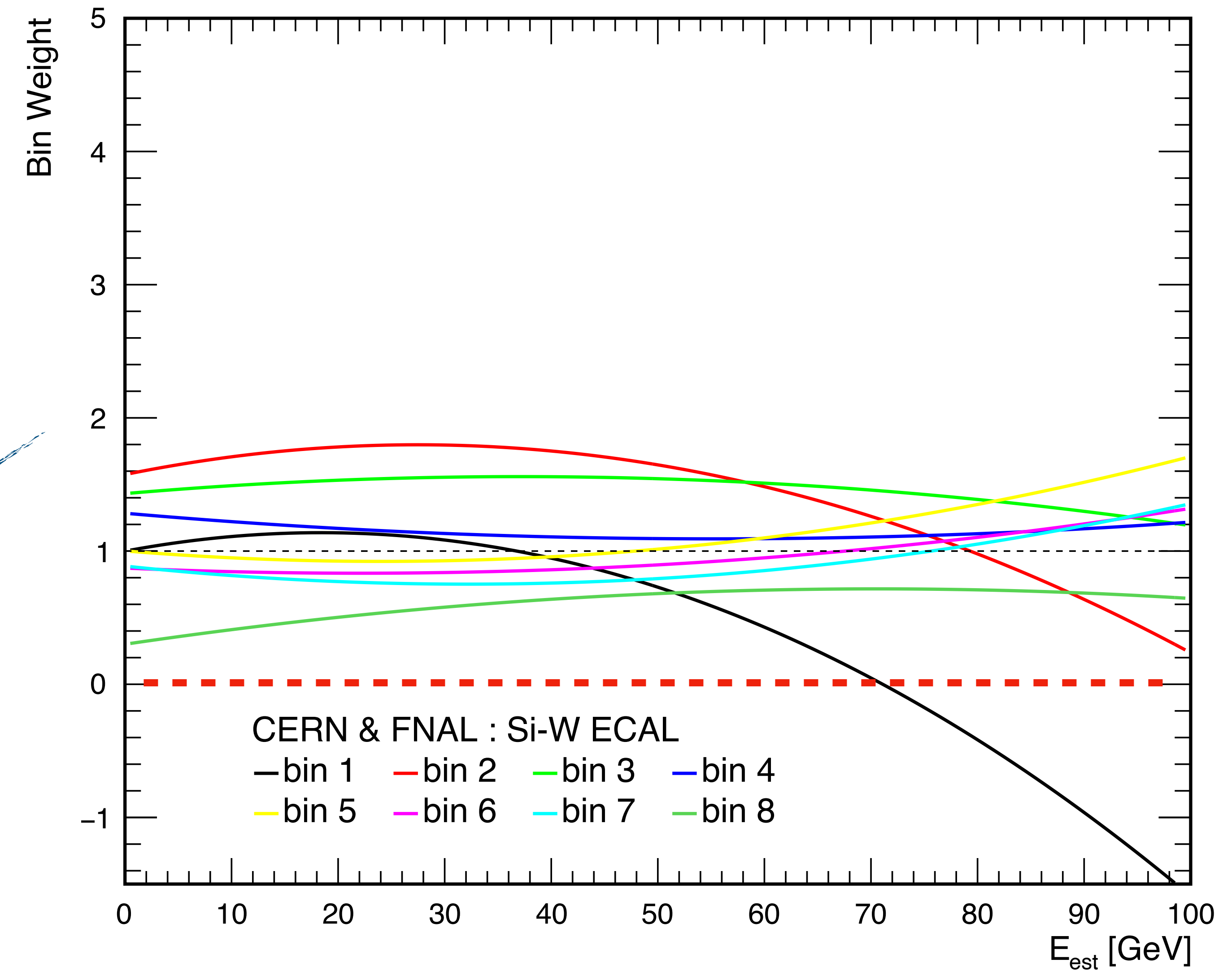

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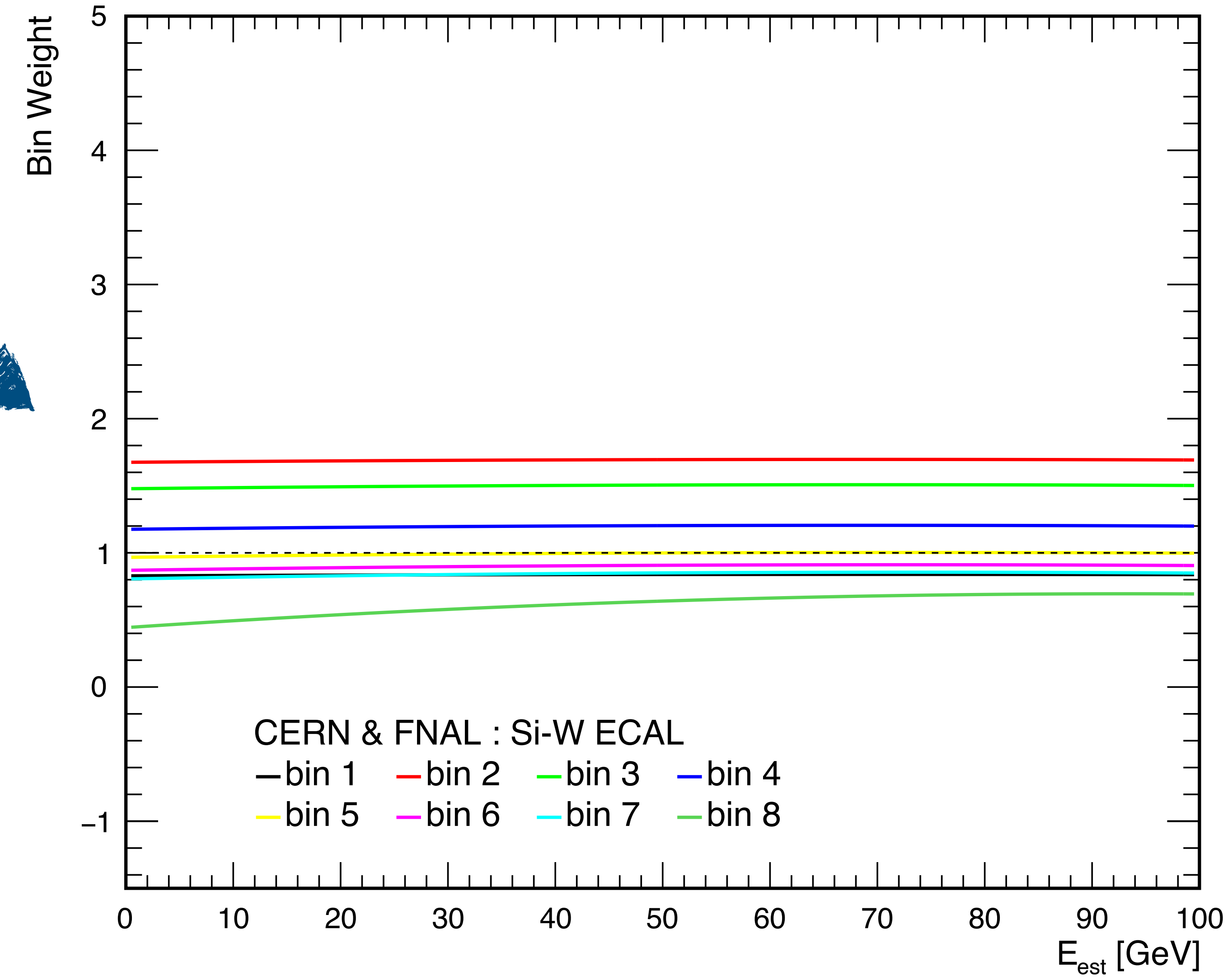
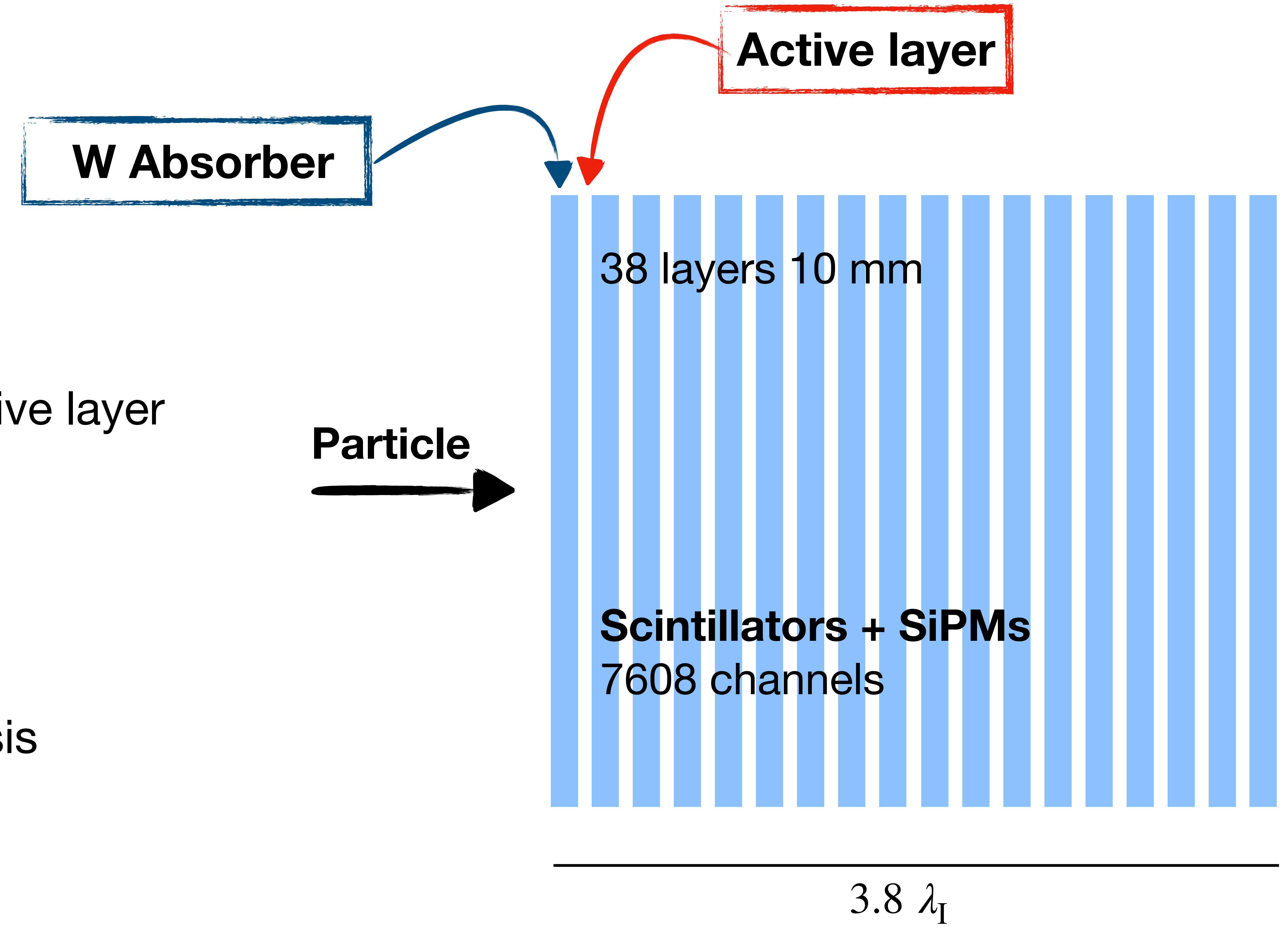


CALICE W-AHCAL

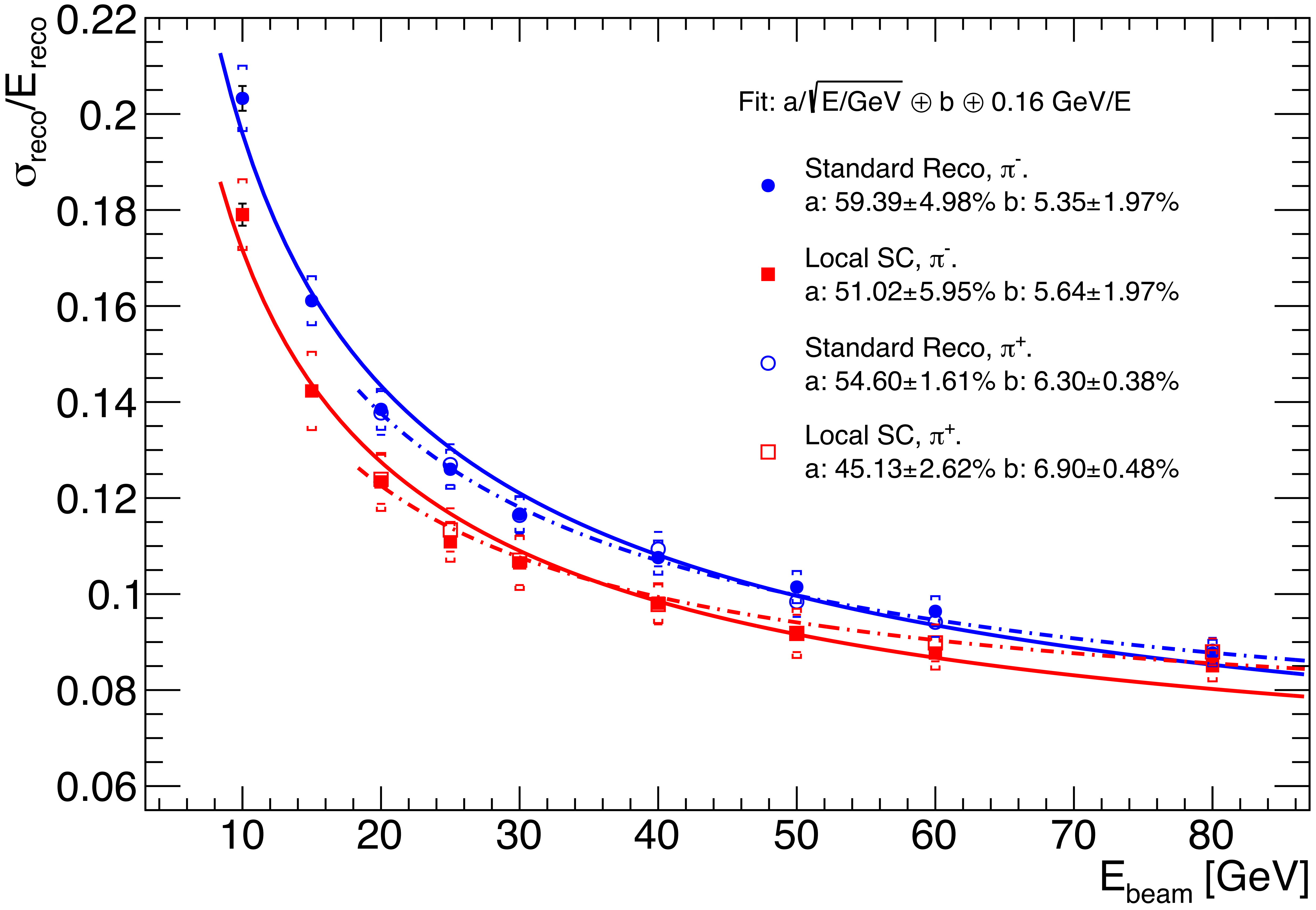
- Sampling calorimeter
- Equipped with tungsten as absorber
- Nearly self compensating
- Prototype was considered for CLIC
- Plastic scintillators combined with SiPMs as active layer



Dataset:

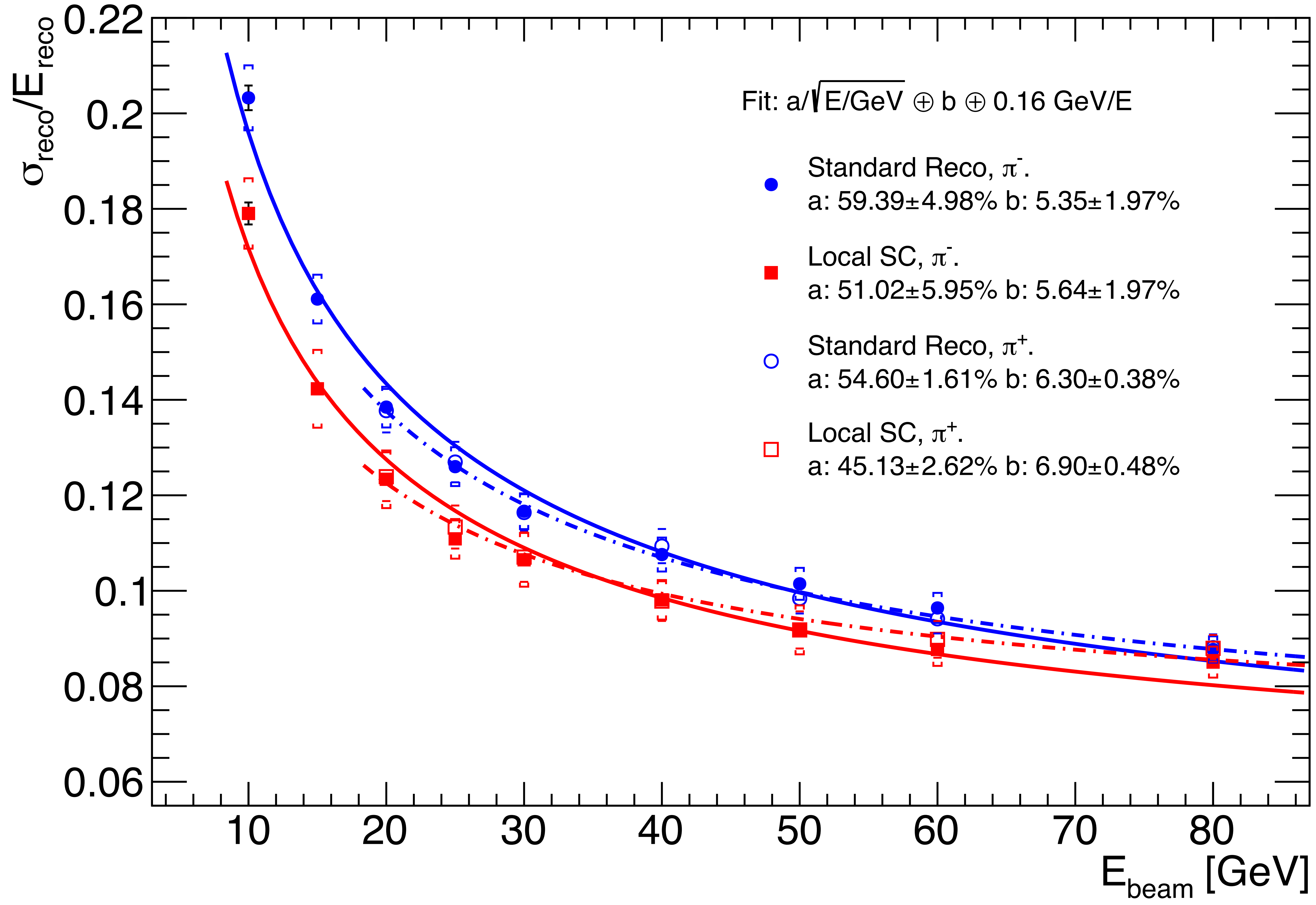
- Recorded at the CERN SPS
- Negative pions from 10 - 80 GeV for main analysis
- Positive pions from 20 - 80 GeV for crosscheck

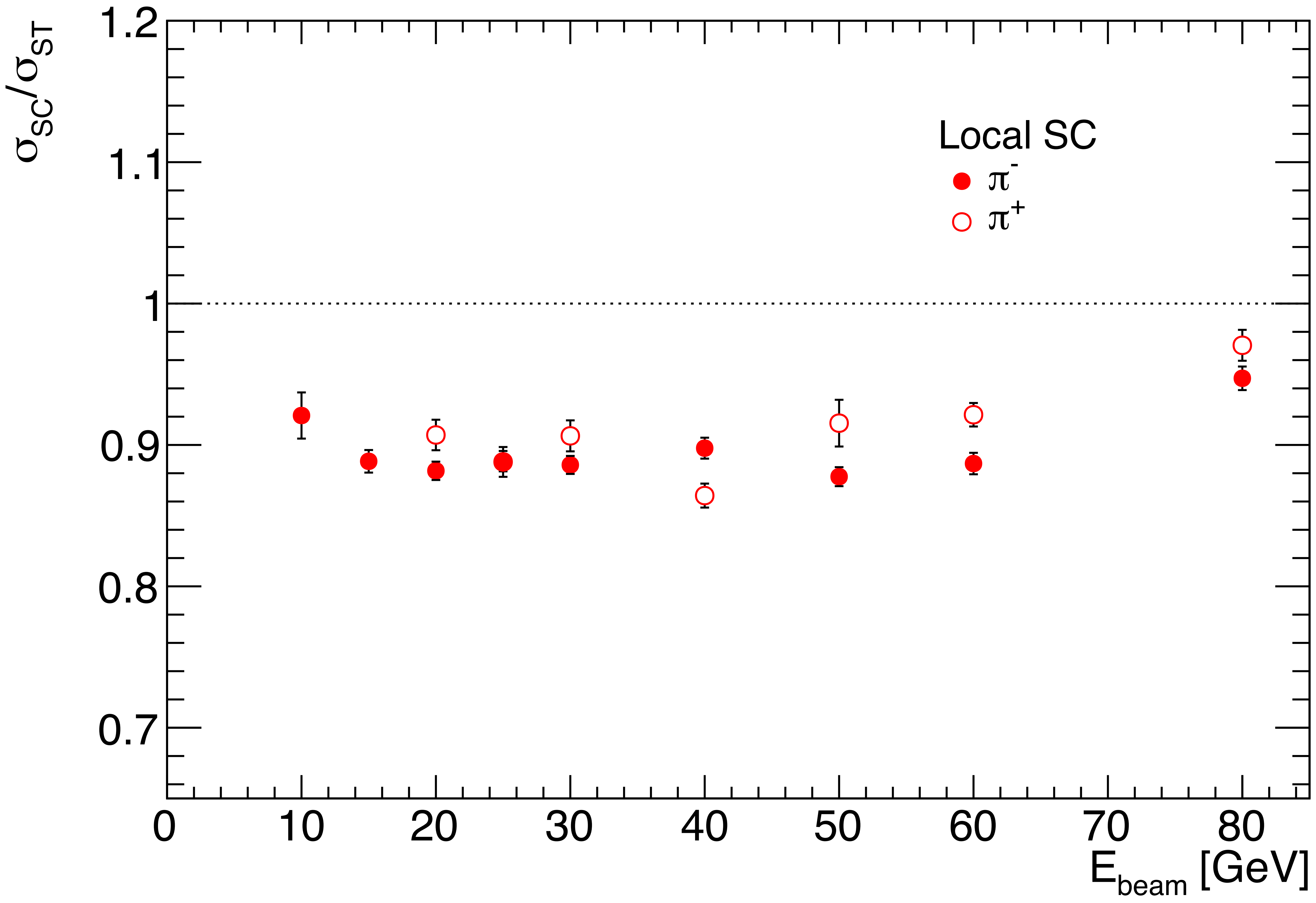
Results W-AHCAL



Fit function: $$\frac{\sigma}{E} = \frac{A}{\sqrt{E}} \oplus \frac{B}{E} \oplus C$$

Results W-AHCAL

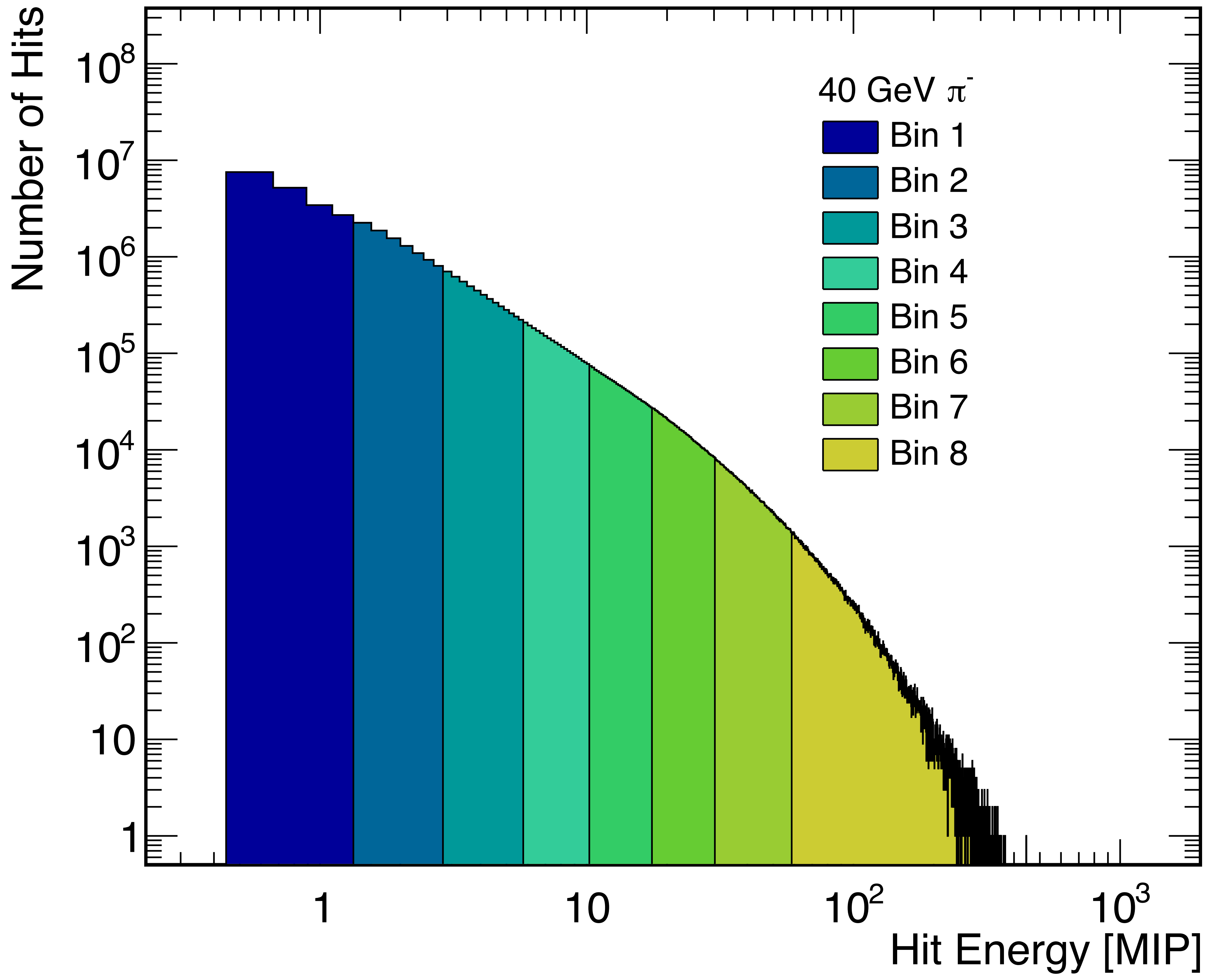


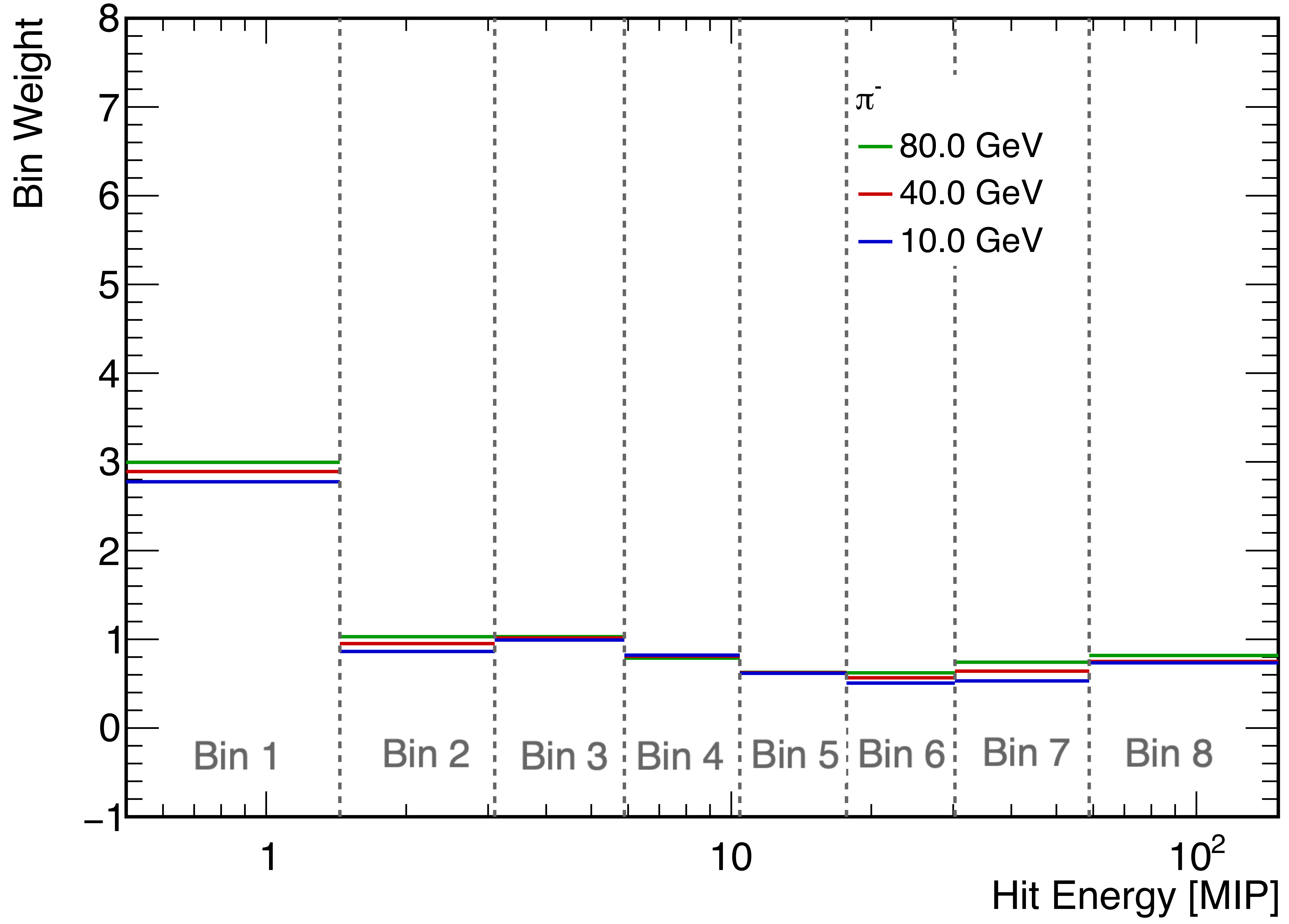


Fit function: $\frac{\sigma}{E} = \frac{A}{\sqrt{E}} \oplus \frac{B}{E} \oplus C$

Improvement of resolution up to 12 %

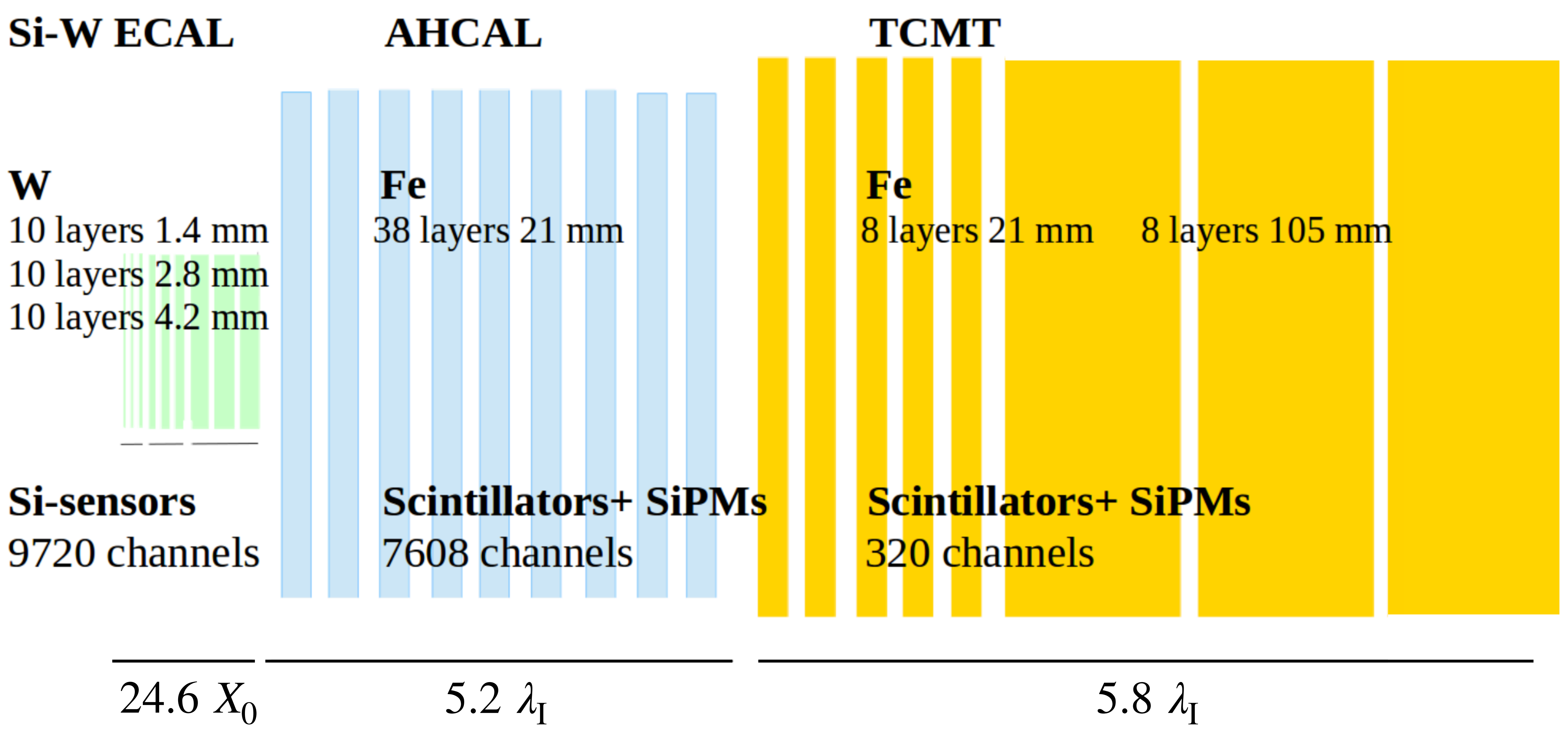
Results W-AHCAL

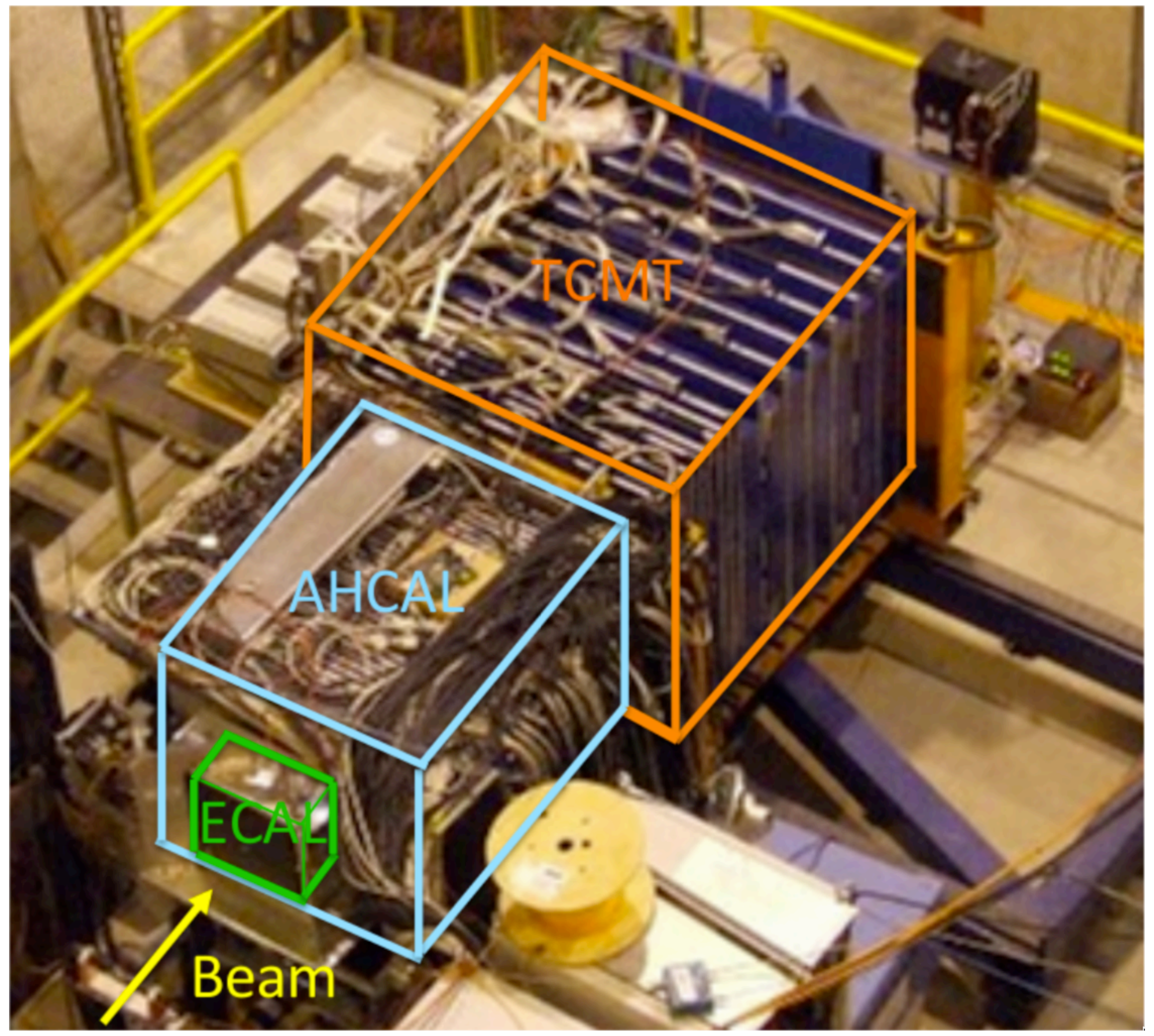




- Main improvement caused by low energetic hits located in the first bin
- W-AHCAL nearly self compensating
- Improvement caused by correcting for fluctuations in hadronic component

CALICE Combined System

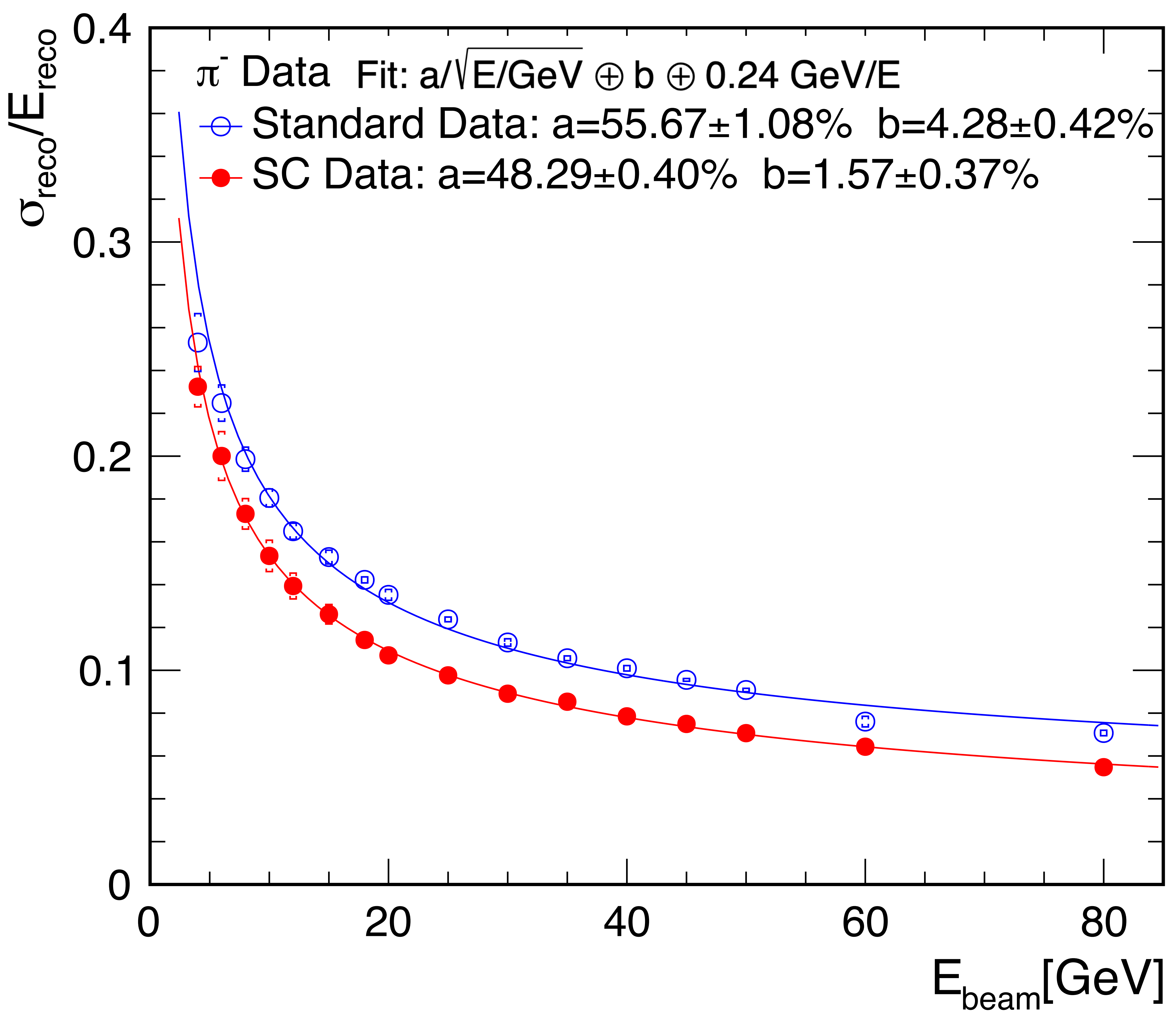




Datasets

- CERN, negative pions 10-80 GeV
- FNAL, negative pions 4-60 GeV
- Monte Carlo (FTFP_BERT, QGSP_BERT) , negative pions 4-80 GeV

Results Combined System



Fit function: $$\frac{\sigma}{E} = \frac{A}{\sqrt{E}} \oplus \frac{B}{E} \oplus C$$

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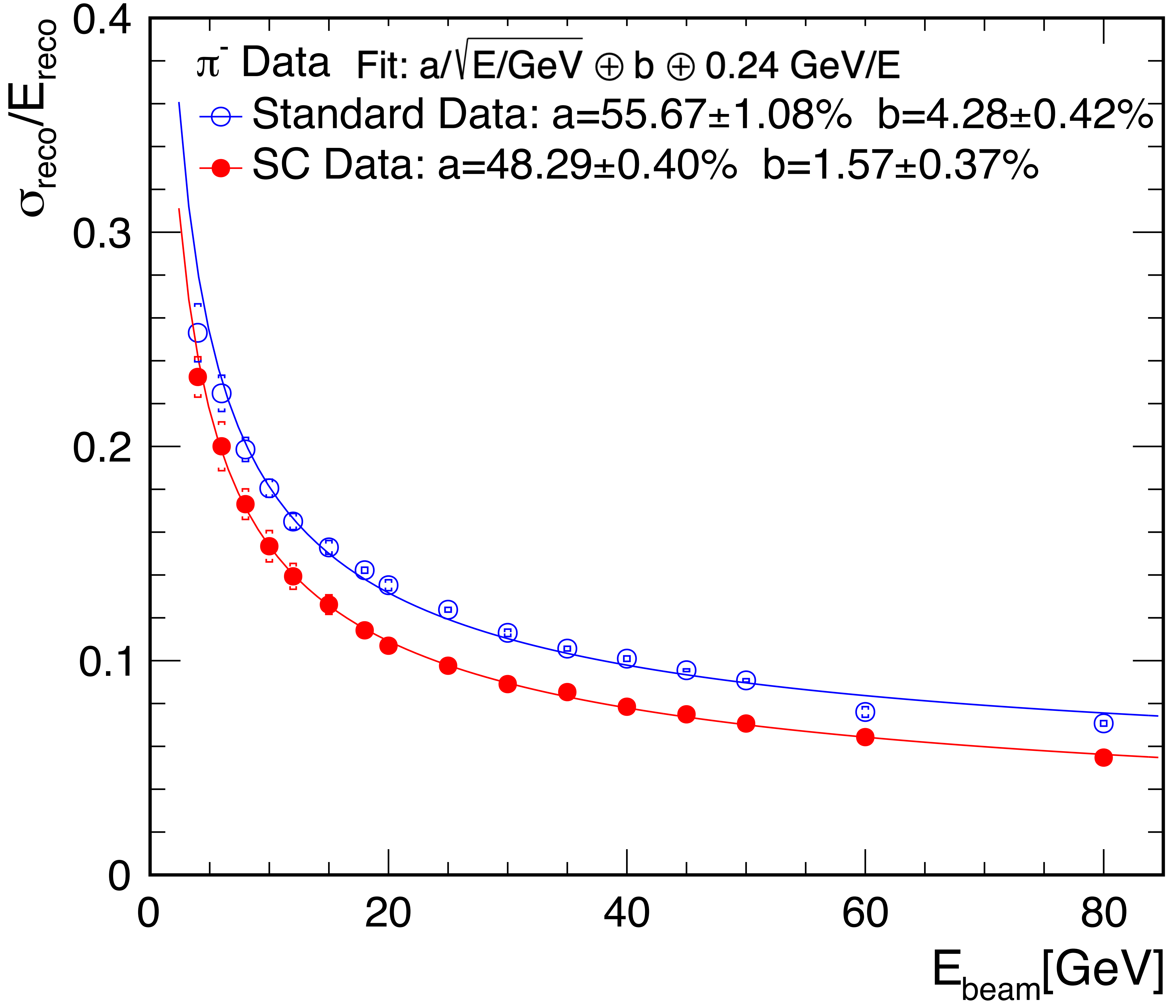
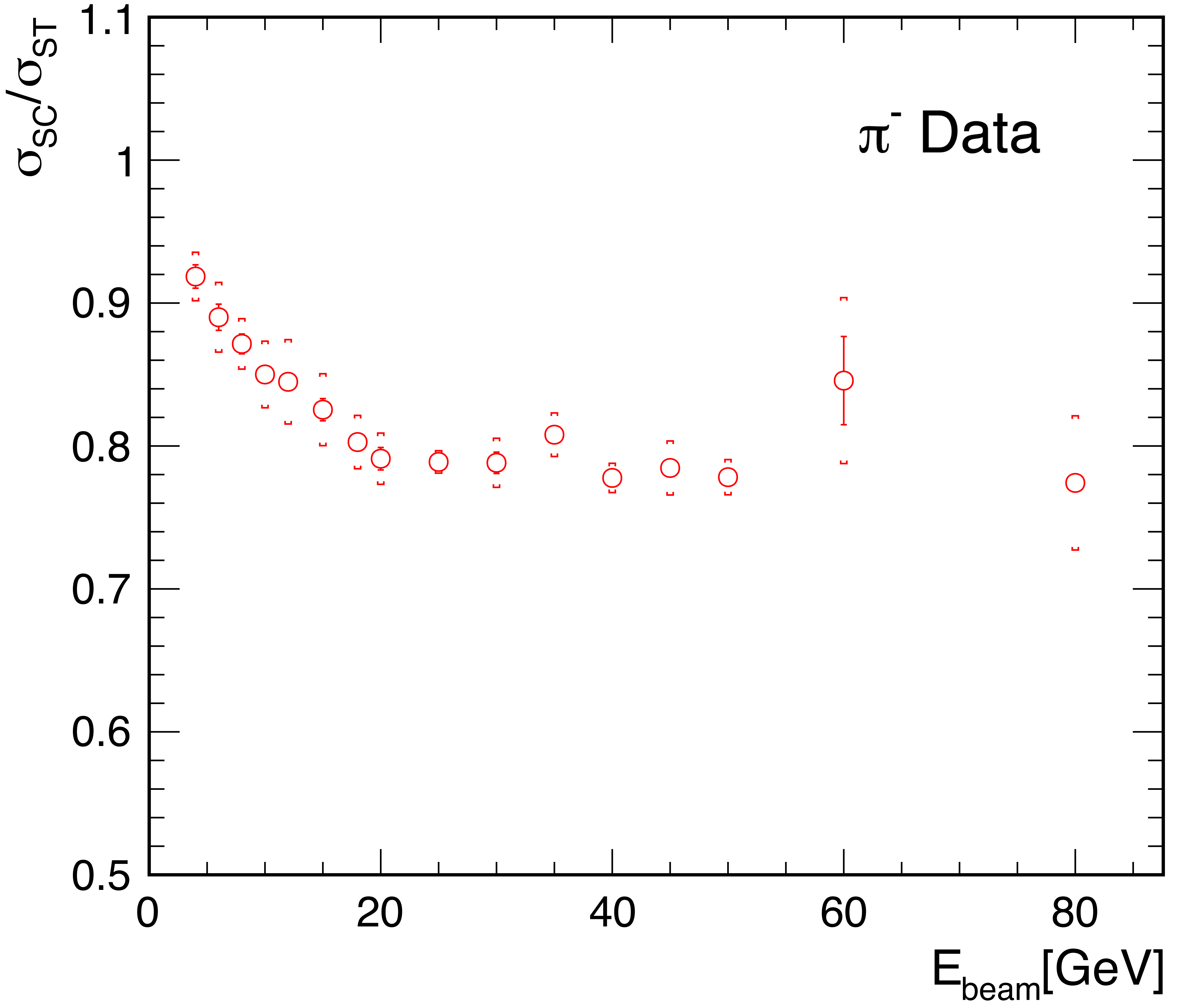


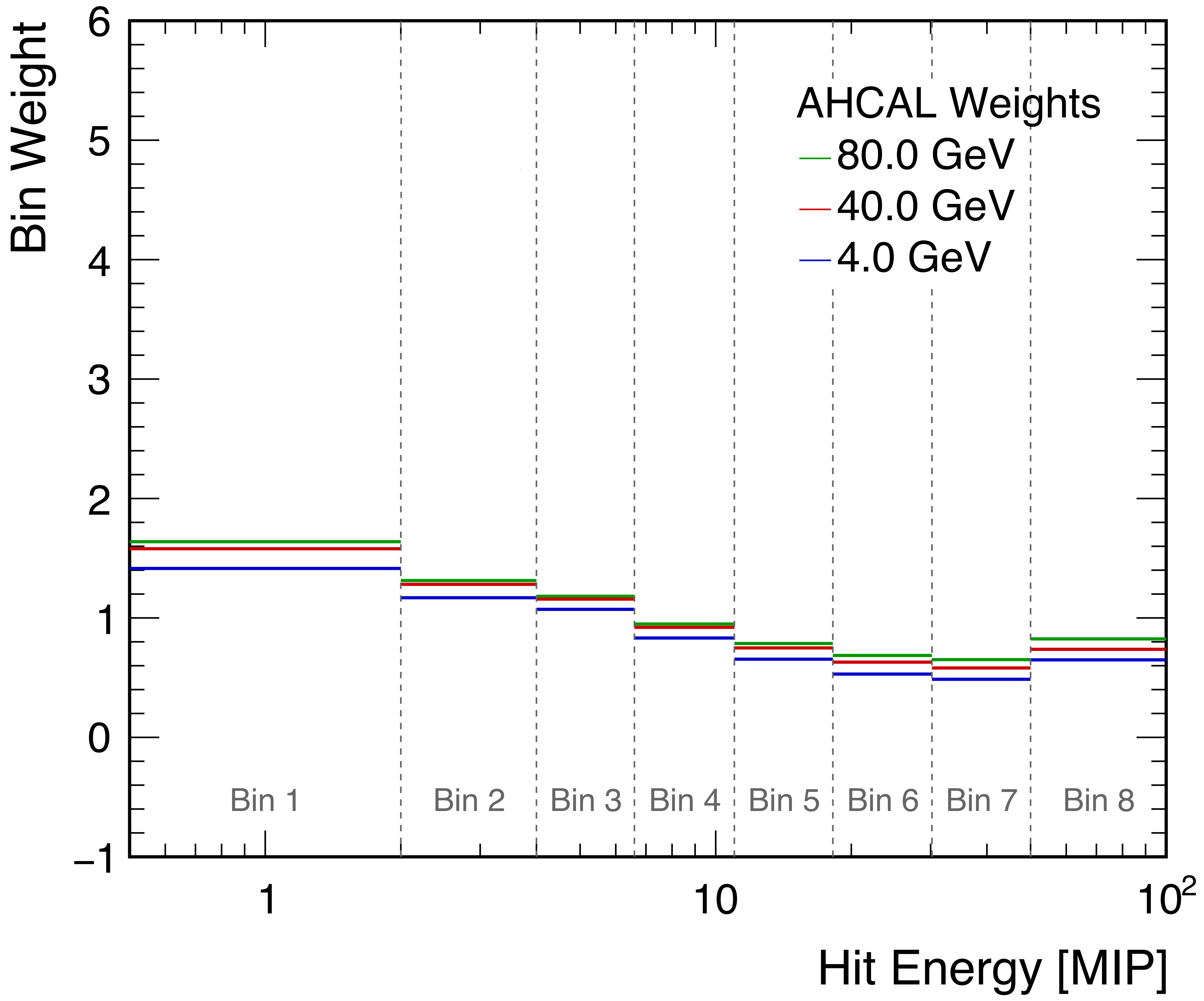


Fit function: $\frac{\sigma}{E} = \frac{A}{\sqrt{E}} \oplus \frac{B}{E} \oplus C$

Improvement up to 23 % for data

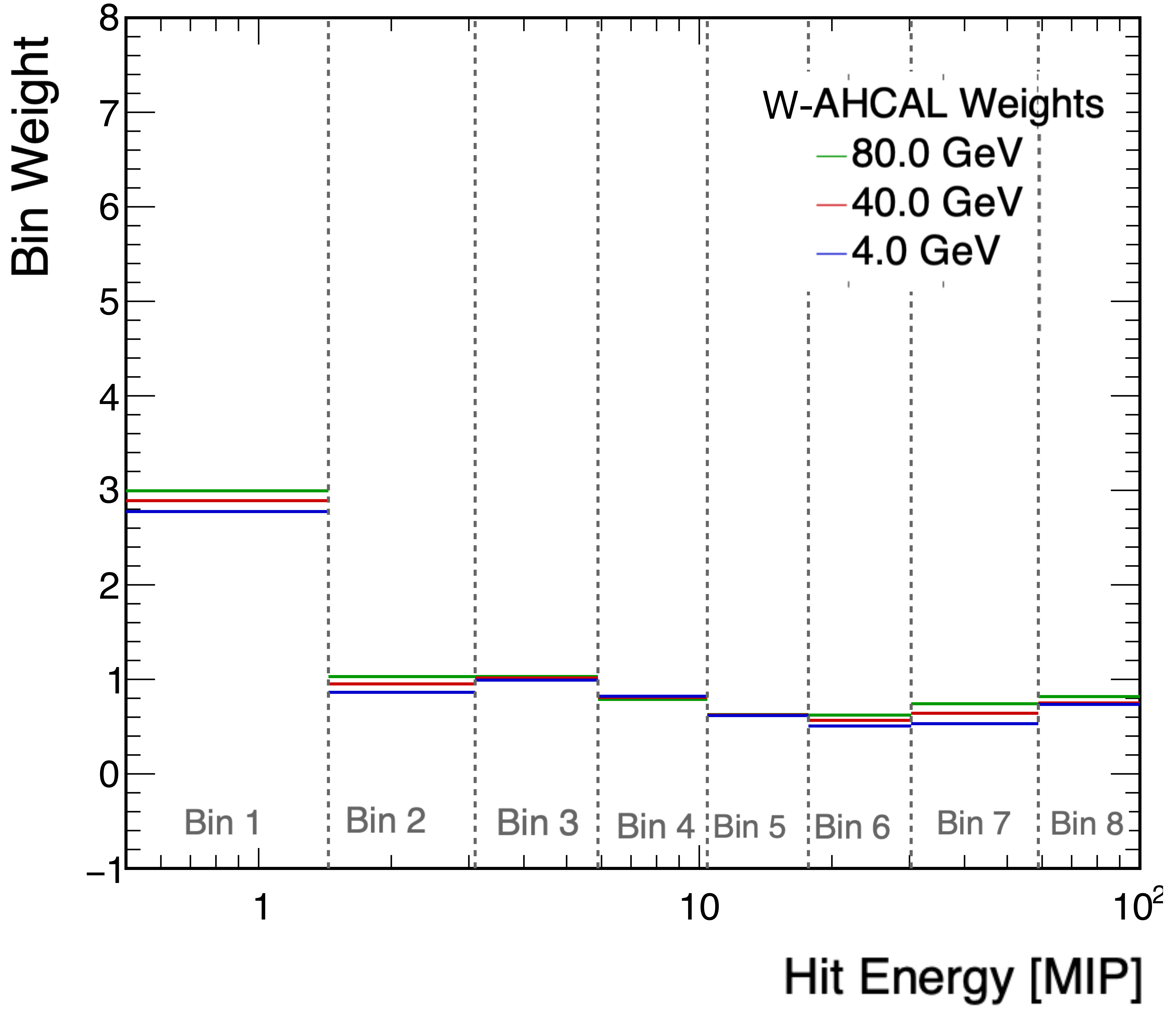
Results Combined System

- Weights change for all bins
- Improvement mainly caused by correcting for fluctuations between electromagnetic and hadronic component

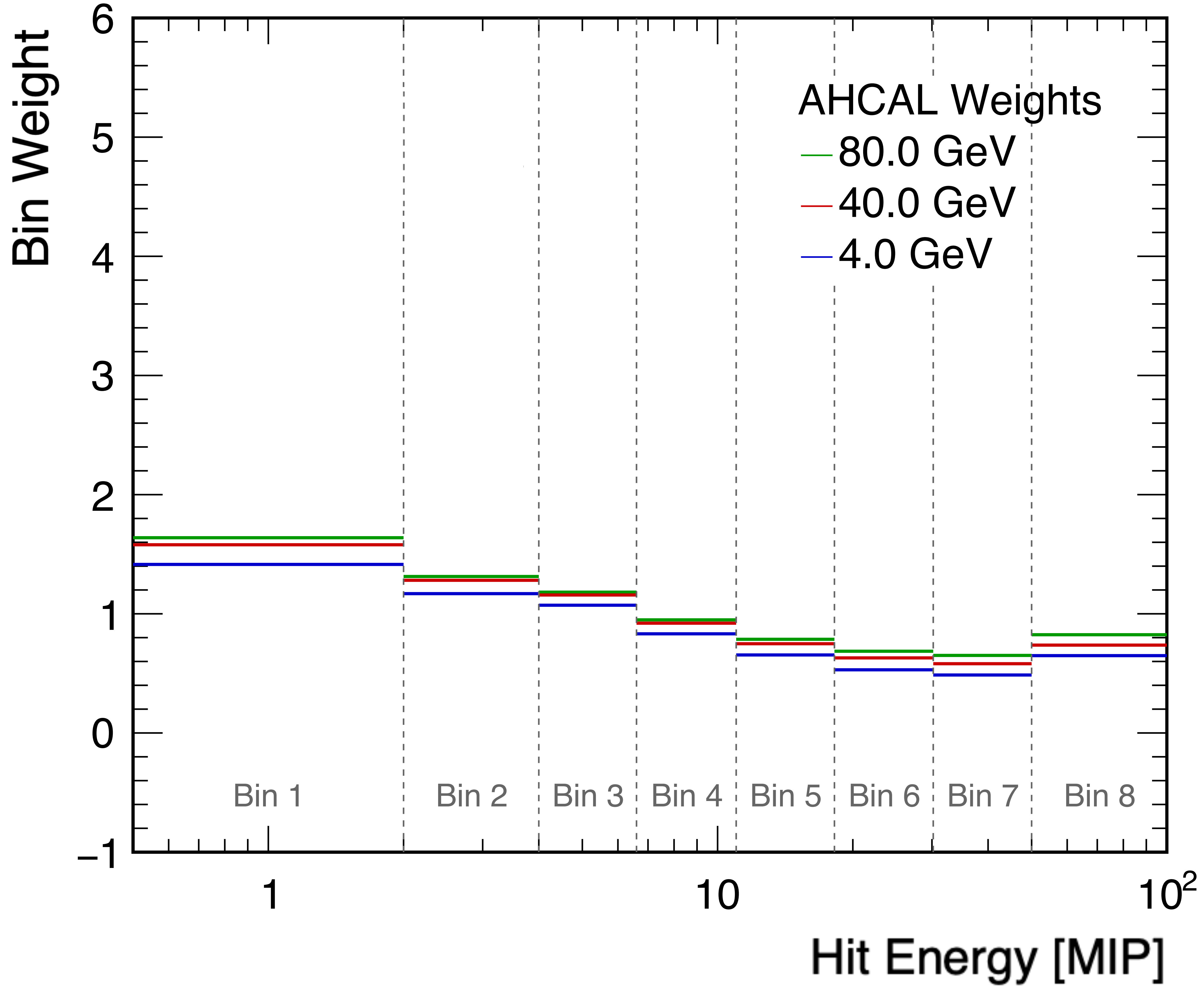


Weight Comparison

W-AHCAL



Combined System



Summary & Outlook

- Physics program at future linear collider requires precise reconstruction of all final states

→**Highly granular calorimeter + Local software compensation**

- Local software compensation with penalty term successfully proven to be a stable method

W-AHCAL:

- Nearly self compensating
- Improvement up to 10 %

Combined calorimeter system:

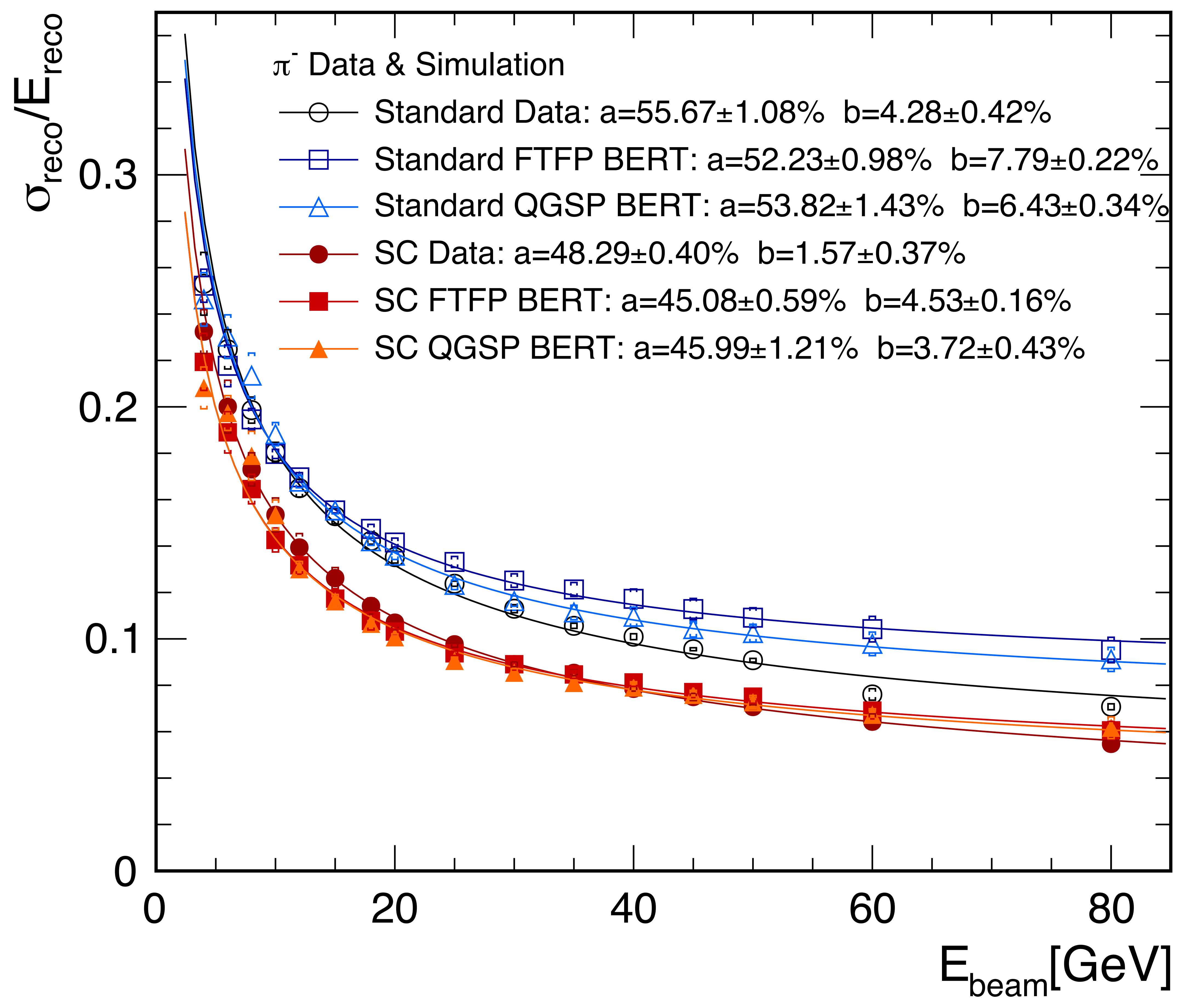
- Improvement up to 23 % for testbeam data

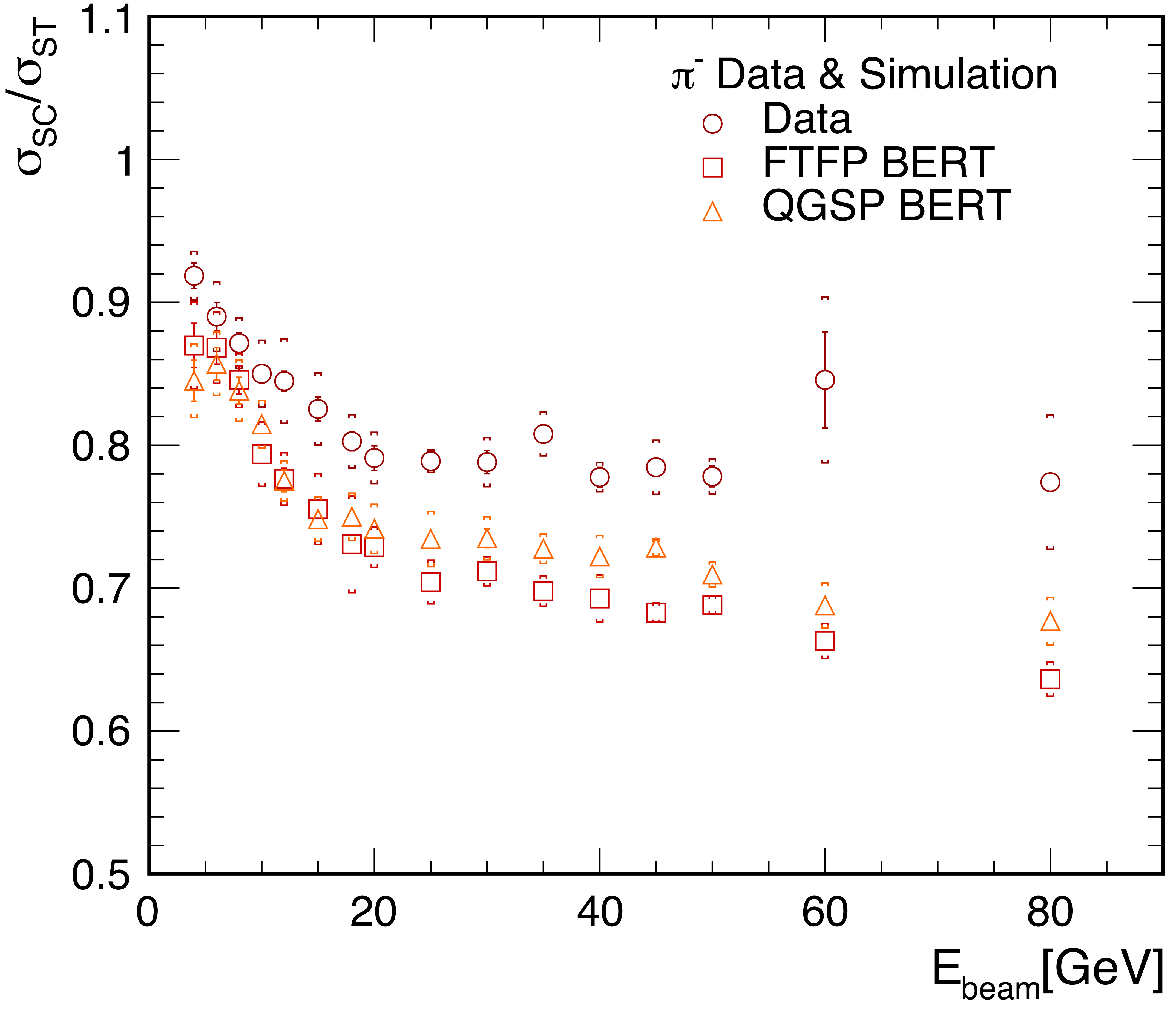
Outlook:

- Data of new prototypes can still be investigated
- Timing of new prototypes provides new dimension to software compensation

Backup

Results Combined System





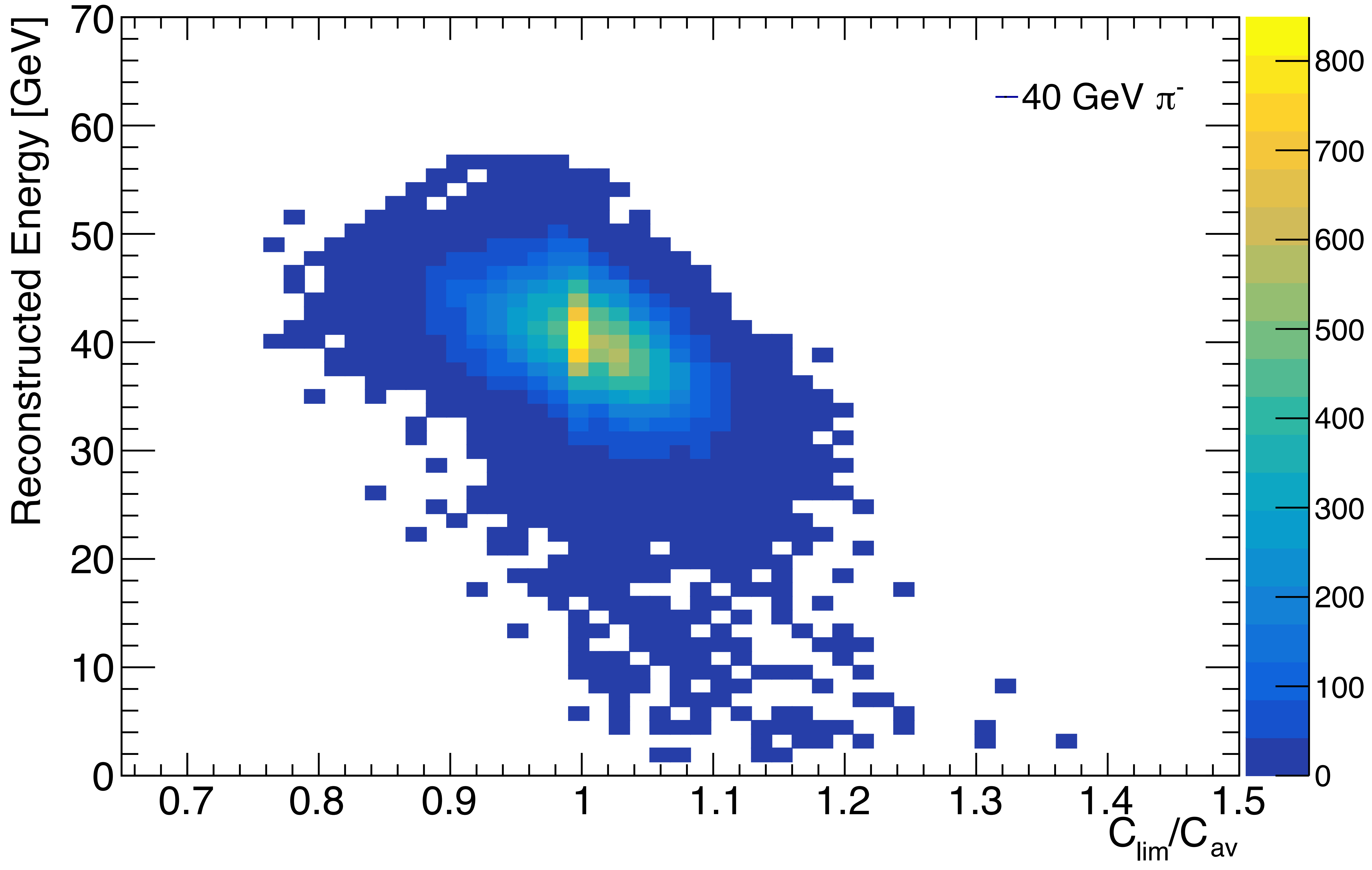
Similar final resolution

Global Software Compensation

- Apply one weight to each event
- Choose threshold to divide hits
- Correction factor is estimated as fraction of hits below threshold
- Free parameter are extracted from fit

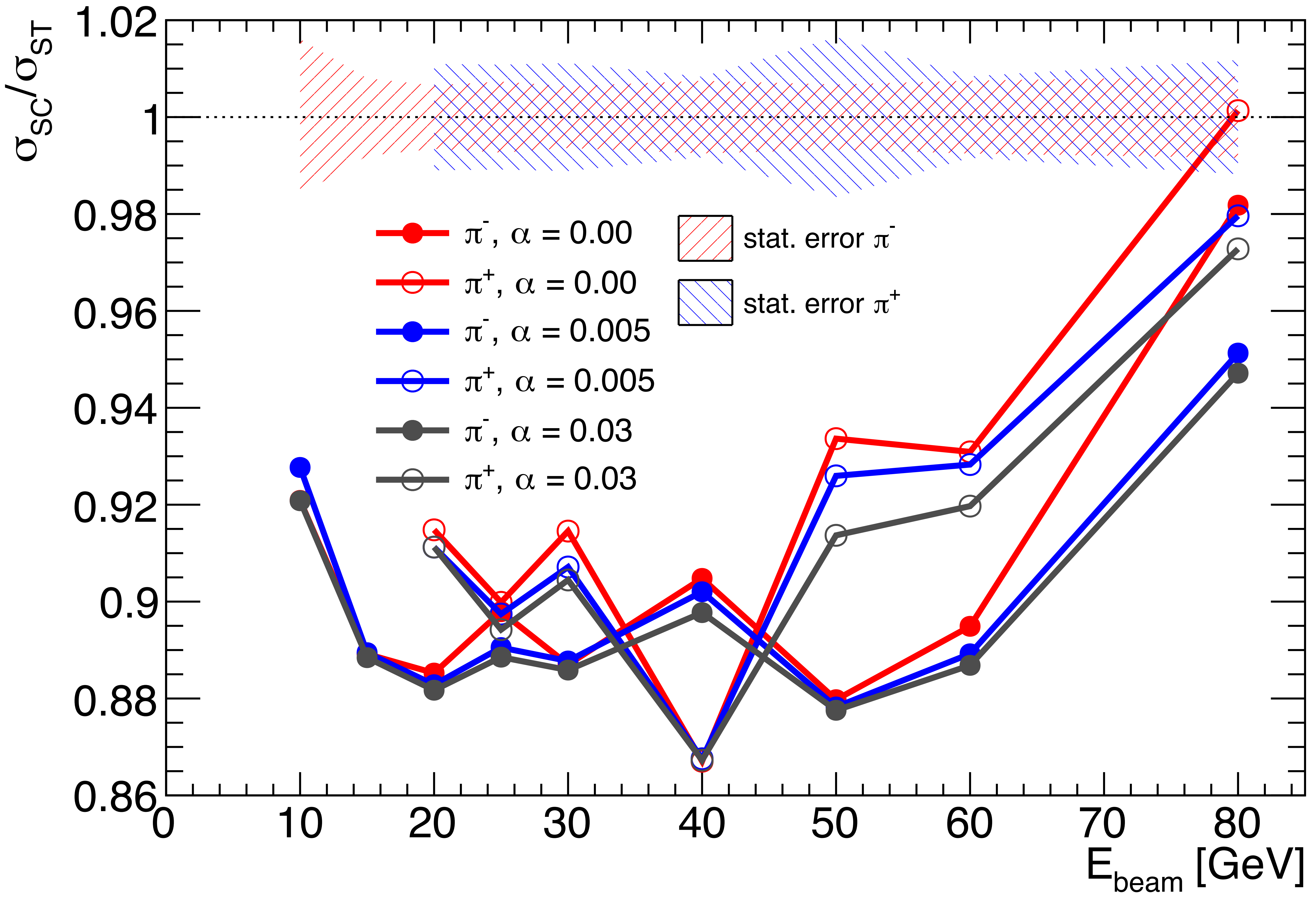
$$E_{sh} = \frac{C_{lim}}{C_{av}} \cdot E_{dep}$$

$$E_{cor} = E_{sh} \cdot (a + b \cdot E_{sh} + c \cdot E_{sh}^2)$$

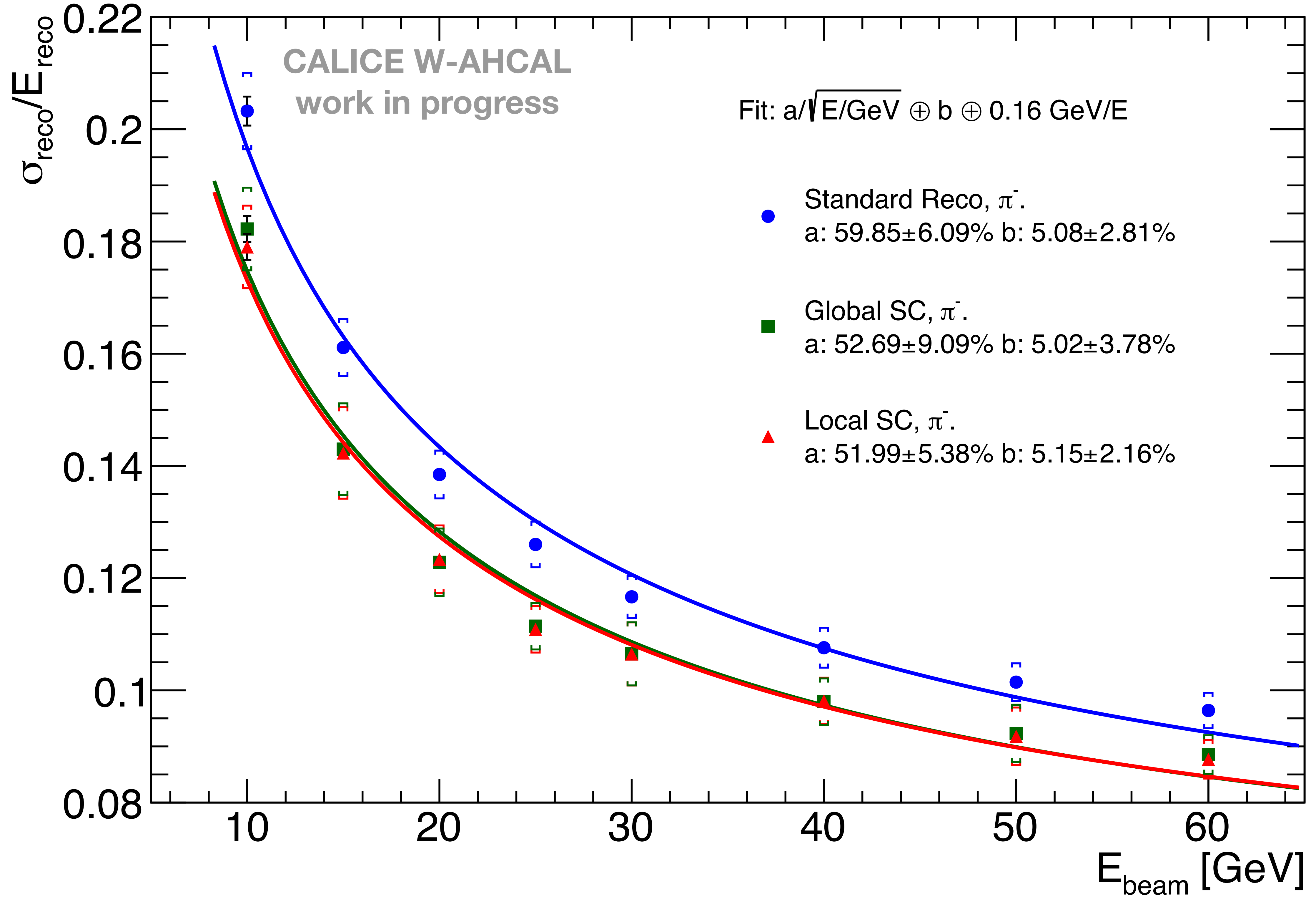


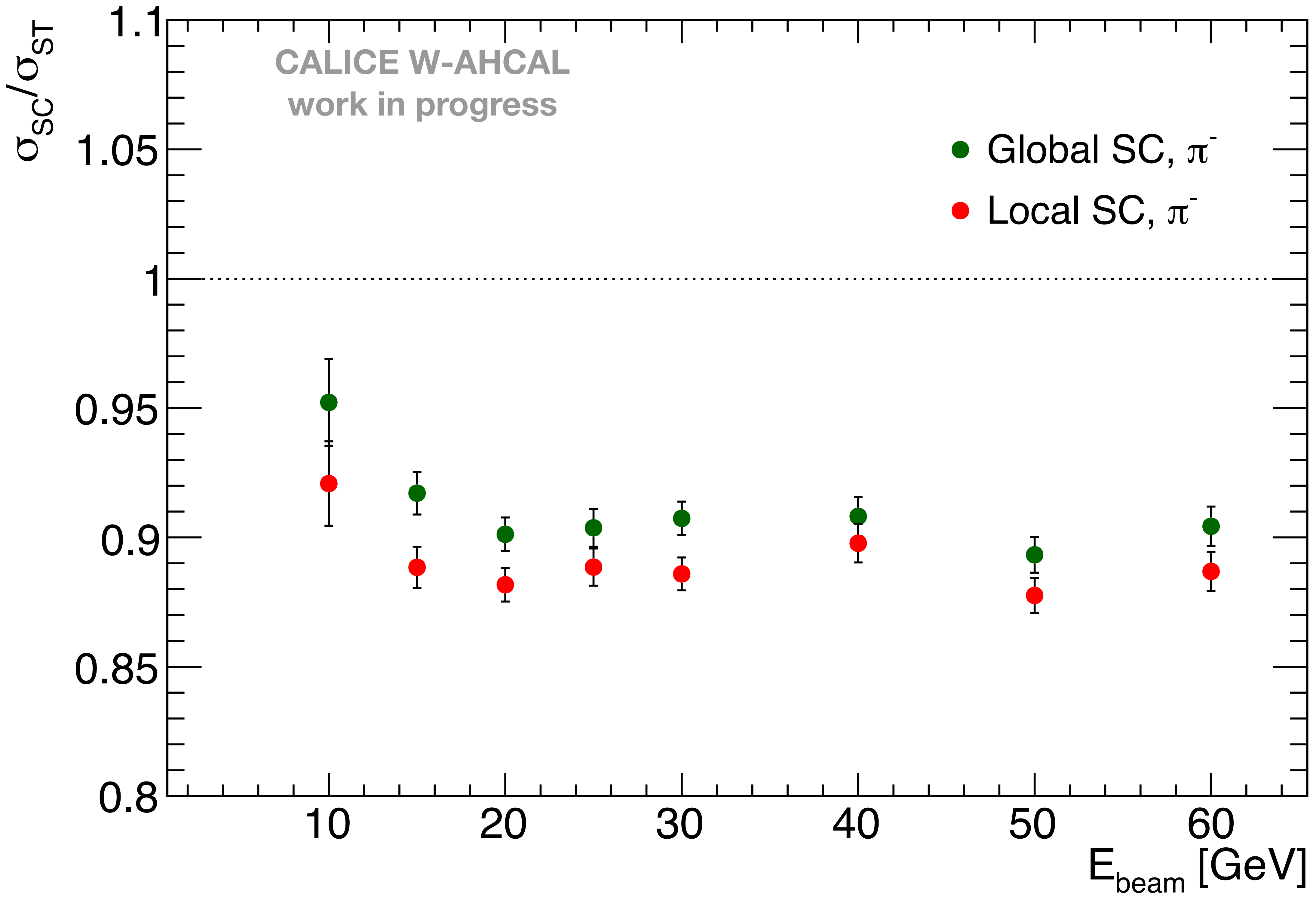
Scaling Factor

- Scaling factor scales contribution of penalty term
- For W-AHCAL: 0.03
- For combined system: 0.1
- Exact value is not important



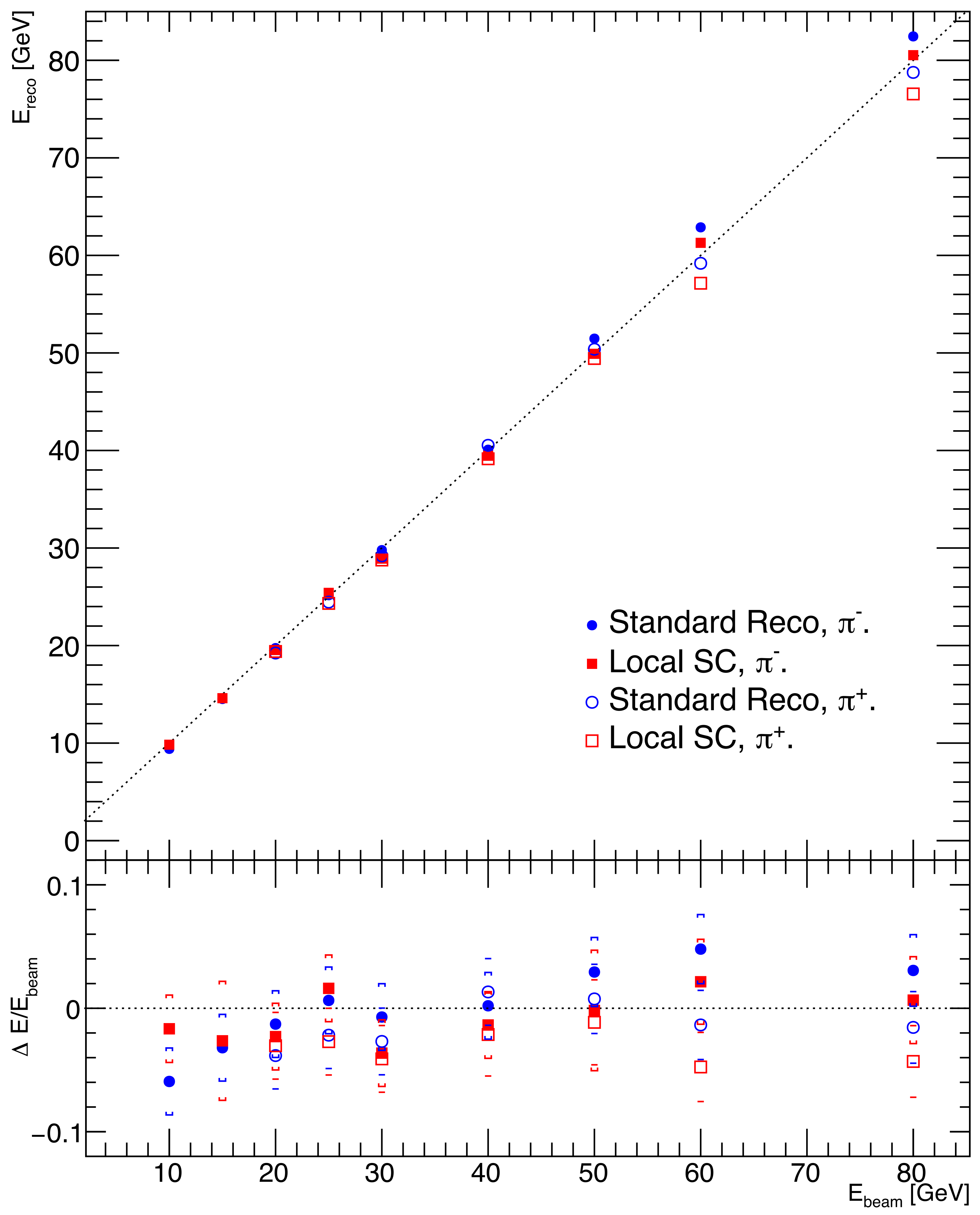
W-AHCAL Global & Local SC



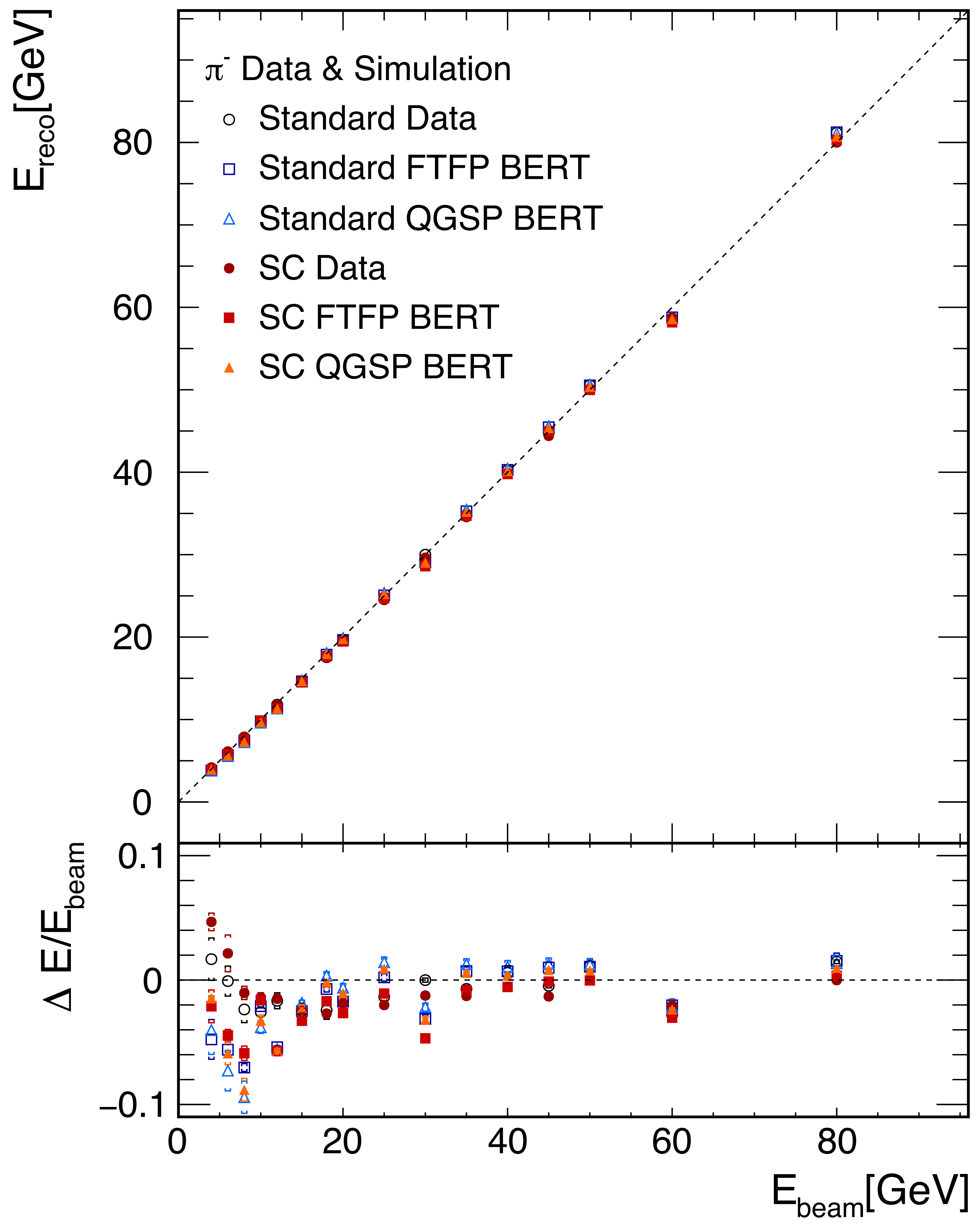


- Only stable performance up to 60 GeV
- Similar performance of both methods

Linearity



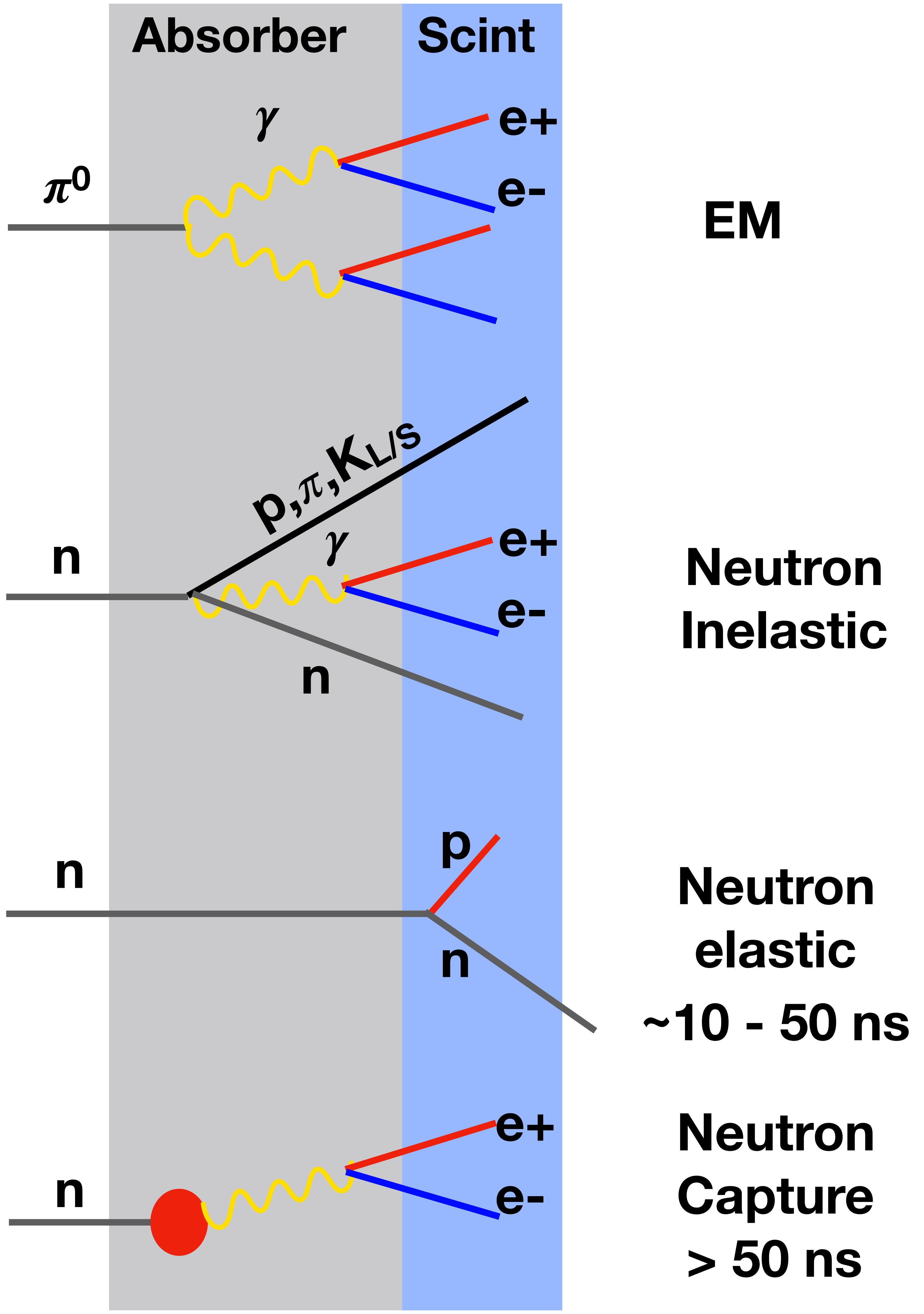
E_{reco} [GeV]
Standard Reco, π^-.
Local SC, π^-.
Standard Reco, π^+.
Local SC, π^+.
$\Delta E/E_{beam}$
E_{beam} [GeV]



π^- Data & Simulation
Standard Data
Standard FTFP BERT
Standard QGSP BERT
SC Data
SC FTFP BERT
SC QGSP BERT
E_{reco}[GeV]
$\Delta E/E_{beam}$
E_{beam}[GeV]

Timing Information

- Reject background
- Improve clustering
- Use in software compensation to identify components of showers



CALICE Prototypes