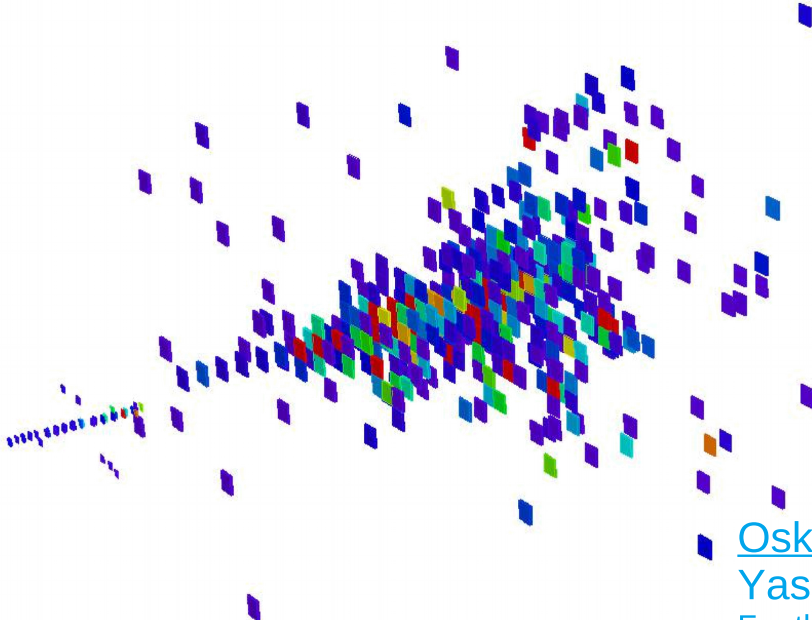
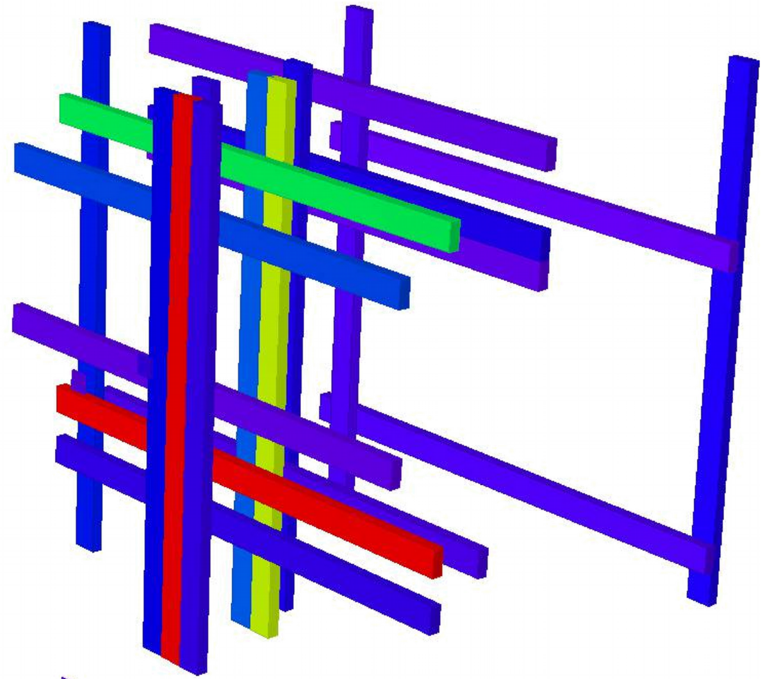
Single Pion Energy Resolutions of combined CALICE Calorimeter Systems

ScECAL + AHCAL + TCMT (CAN-056)

SiWECAL + AHCAL + TCMT (CAN-058)





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For the CALICE Collaboration

IAS HEP, HKUST, Hong Kong
01/18/2018

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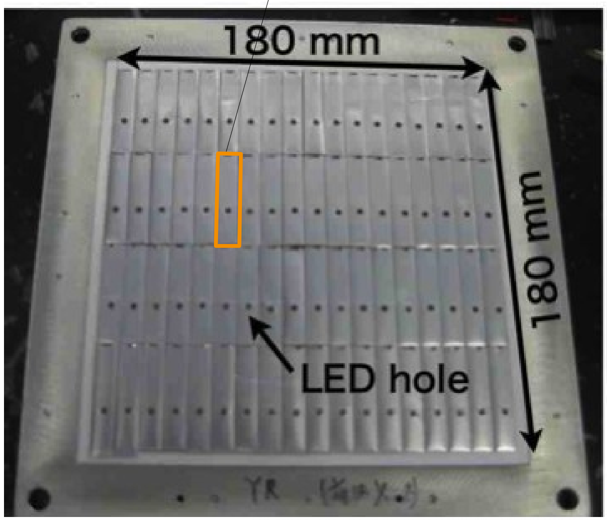
CALICE Scintillator-SiPM Physics Prototype System

ScECAL

Scintillator Electromagnetic Calorimeter

45*10mm²



SiPMs: Hamamatsu

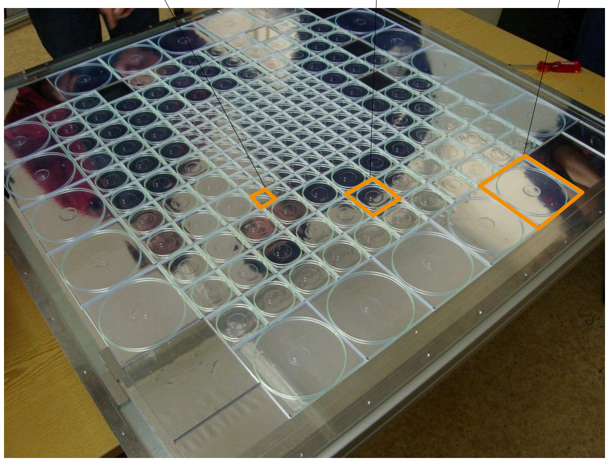
AHCAL

Analog Hadronic Calorimeter

60*60mm²

30*30mm²

120*120mm²

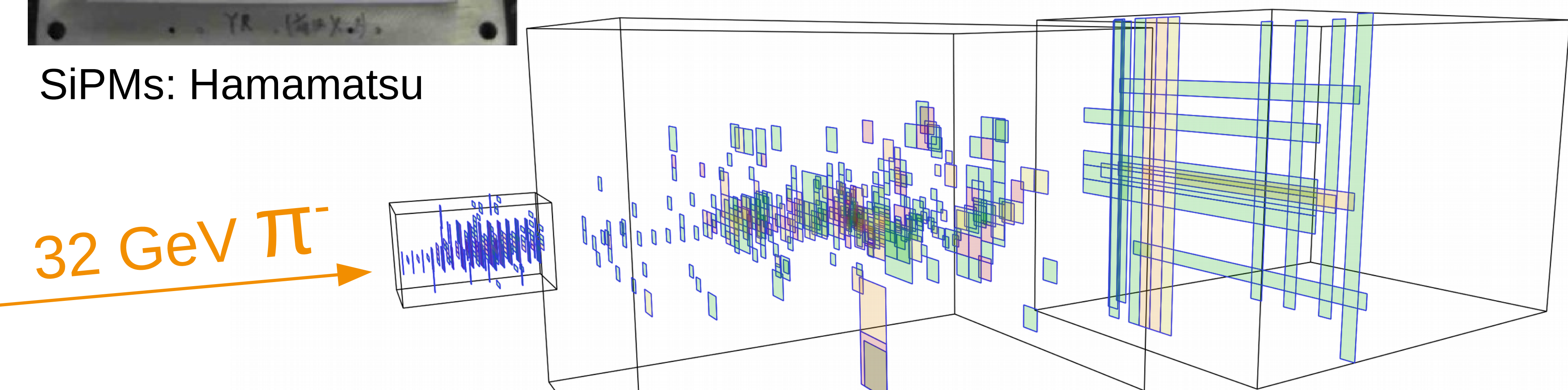


TCMT

Tail Catcher & Muon Tracker

1000*50mm²

SiPMs: MePhI Pulsar



Testbeam Analysis

> Energy reconstruction in combined calorimeter systems
  - Longitudinally varying sampling
  - Making use of granularity apart from particle flow

	ScECAL	AHCAL	TCMT
Absorber material	3.5mm W	21mm Fe	21mm (105mm) Fe
Scint. thickness	3mm	5mm	5mm
Sampling fraction (EM)	1/17	1/33	1/33 (1/165)

> **Energy resolution of the combined system?**

> **Energy resolution well described in MC?**

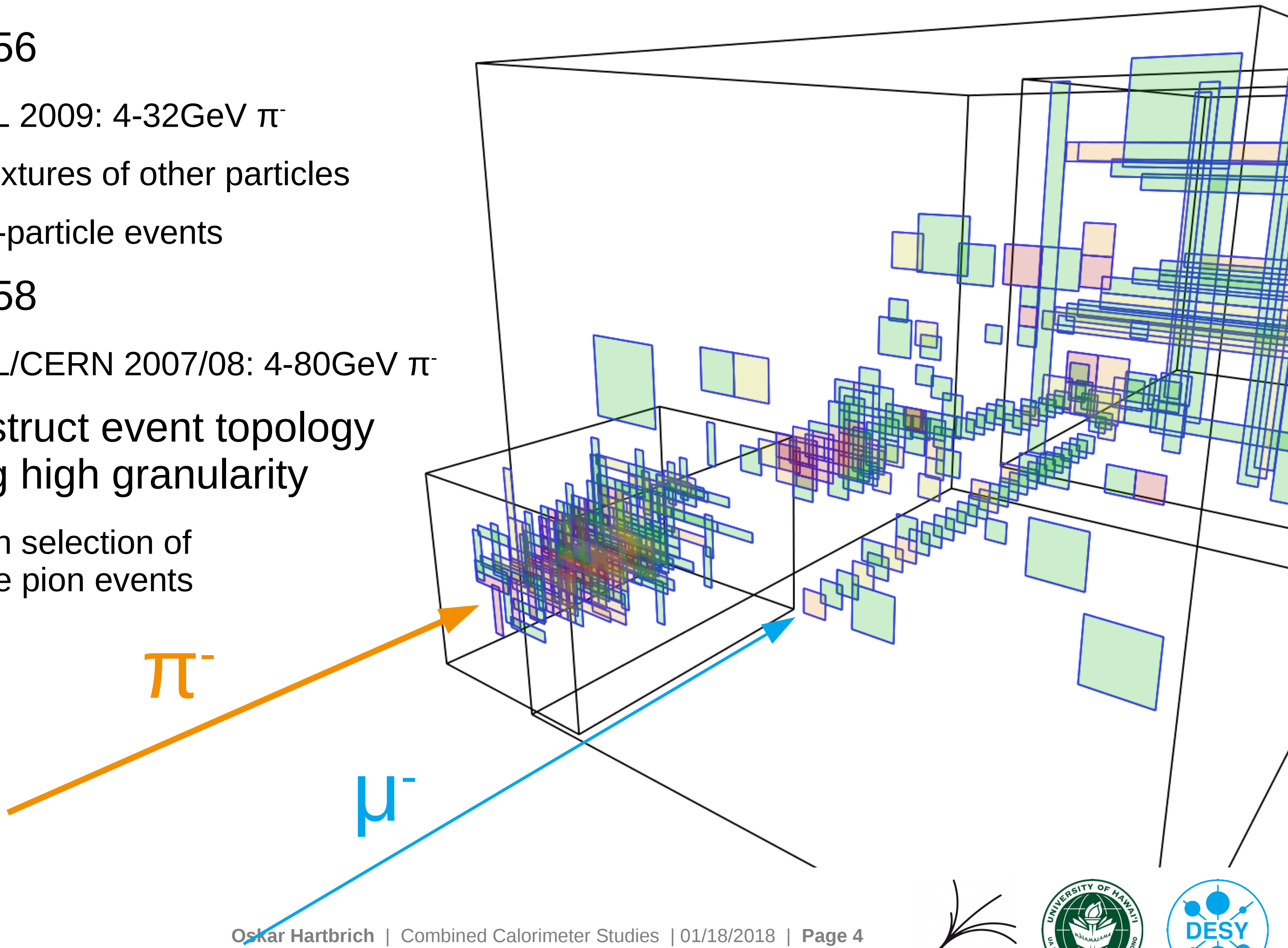
> **How is the energy resolution influenced by ScECAL?**

Event Samples

> CAN-056
  - FNAL 2009: 4-32GeV π^-
  - Admixtures of other particles
  - Multi-particle events

> CAN-058
  - FNAL/CERN 2007/08: 4-80GeV π^-

> Reconstruct event topology using high granularity
  - Clean selection of single pion events



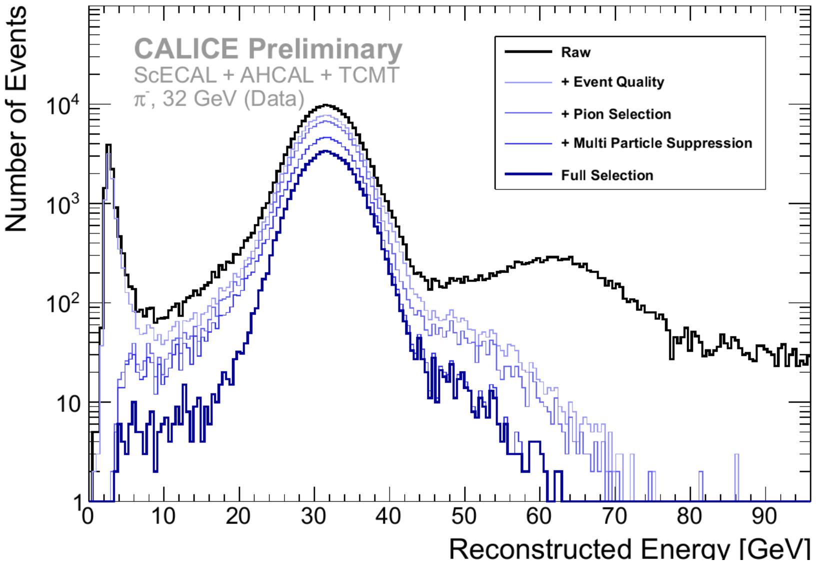
Event Selection

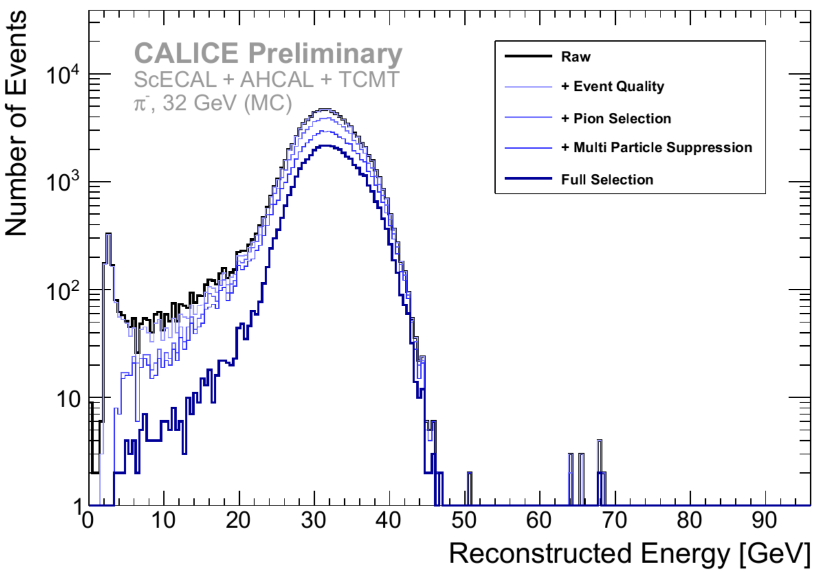
> Pion selection
  - Beamline instrumentation
  - First hadron interaction layer (FHI) ≥ 5
    (4 ScECAL layers as preshower detector)
  - No tracks parallel to beam axis

> Single particle selection
  - Single, isolated primary track

> Shower start selection
  - FHI ≤ 5th layer AHCAL
    (consistent with previous analyses)

> Efficiencies and biases from MC
  - No bias on EM-subshower fraction
  - No bias on response/resolution





Energy Reconstruction - Standard

> Standard reconstruction: Single constant weight per calo (~1/sampling)

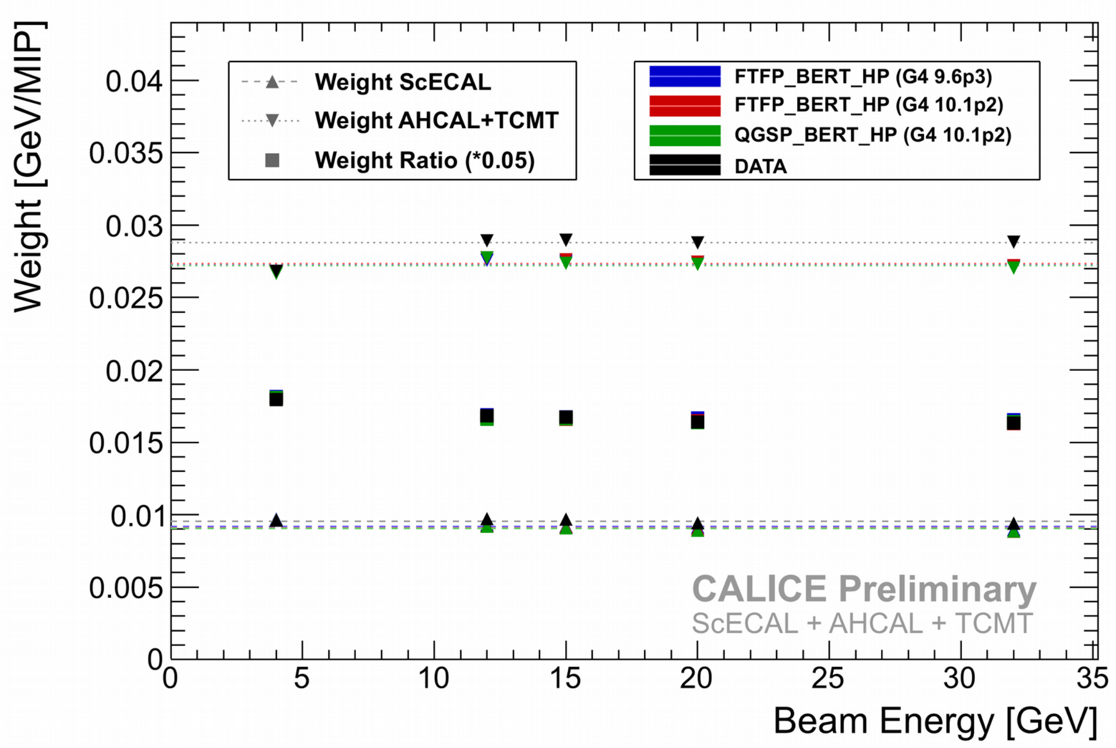
$$E_{\text{rec}}^{\text{classic}} = w_{\text{ECAL}} \left(E_{\text{sum}}^{\text{ECAL}}\right) + w_{\text{HCAL}} \left(E_{\text{sum}}^{\text{HCAL}} + E_{\text{sum}}^{\text{TCMT}}\right)$$

> Weights from χ^2 optimisation

$$\chi^2 = \frac{(E_{\text{rec}} - E_{\text{beam}})^2}{(\sigma_E)^2}$$

> Similar weights in data and simulation

- 5% shift from deposition overestimation in MC
- Ratio identical in data/MC

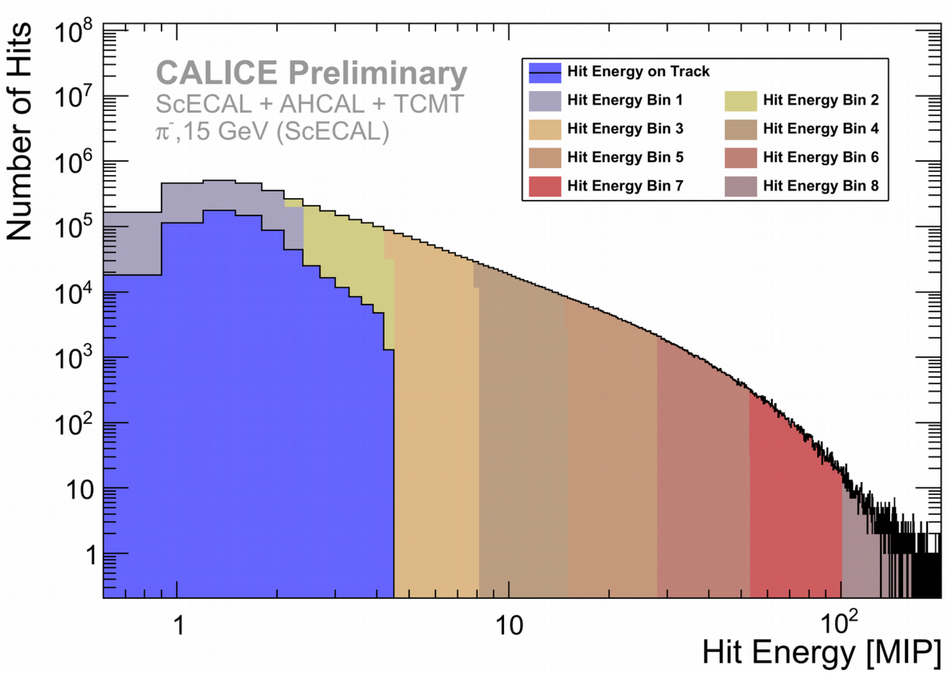


Energy Reconstruction – Software Compensation

- Mean deposition of electrons higher than hadrons
  - e/h ratio > 1 (depending on absorber, active material, geometry)
- Hadron shower: variable energy fraction in EM subshowers
  - Identification of EM subshowers from local deposition density

Software Compensation

- Weight each hit in reconstruction
  - Depending on hit energy
  - As function of full shower energy
- Hit energy in 8 bins
  - Primary track hit weighted separately

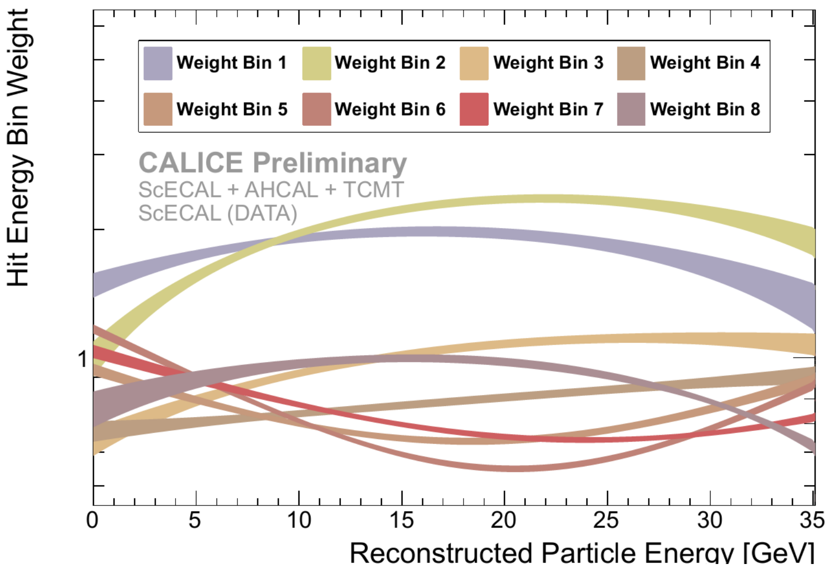


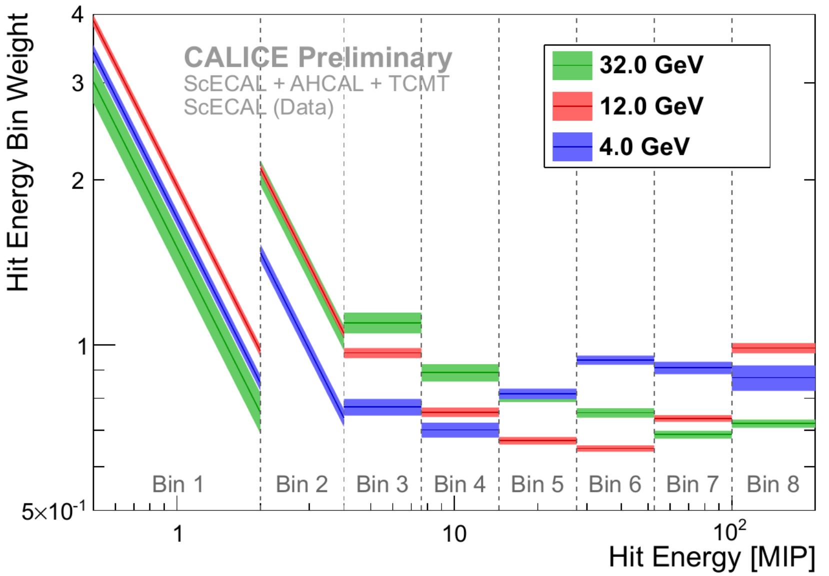
Energy Reconstruction – Software Compensation Weights

> Bin weights parametrised with beam energy
  - 2nd order polynomial, 3 free parameters

> Binary reconstruction in Bins 1-2
  - Only counting number of hits in bin
  - Suppression of Landau fluctuations

> Minimum weight bin energy increases with energy
  - Typical EM hit energy depends on shower energy



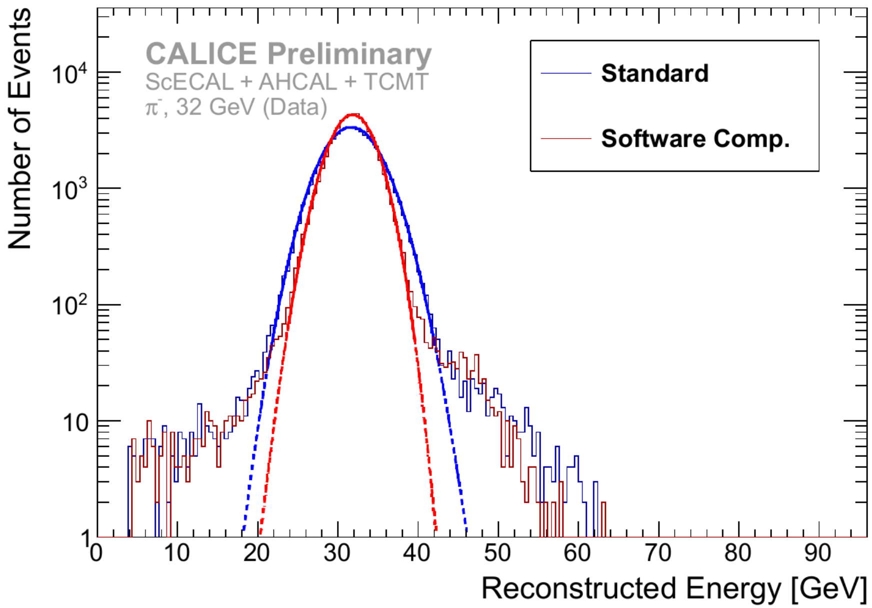


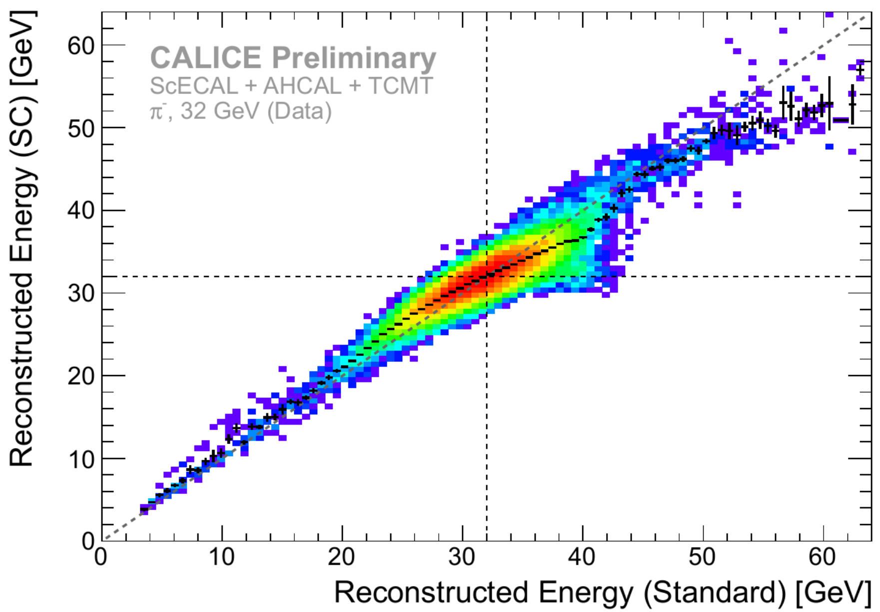
Software Compensation – Resolution Improvement

> Strong resolution improvement from software compensation
  - AHCAL: e/h ≈ 1.2
  - Very small change in mean reconstructed energy

> Too low standard reconstructed energies weighed up

> Too high standard reconstructed energies weighed down

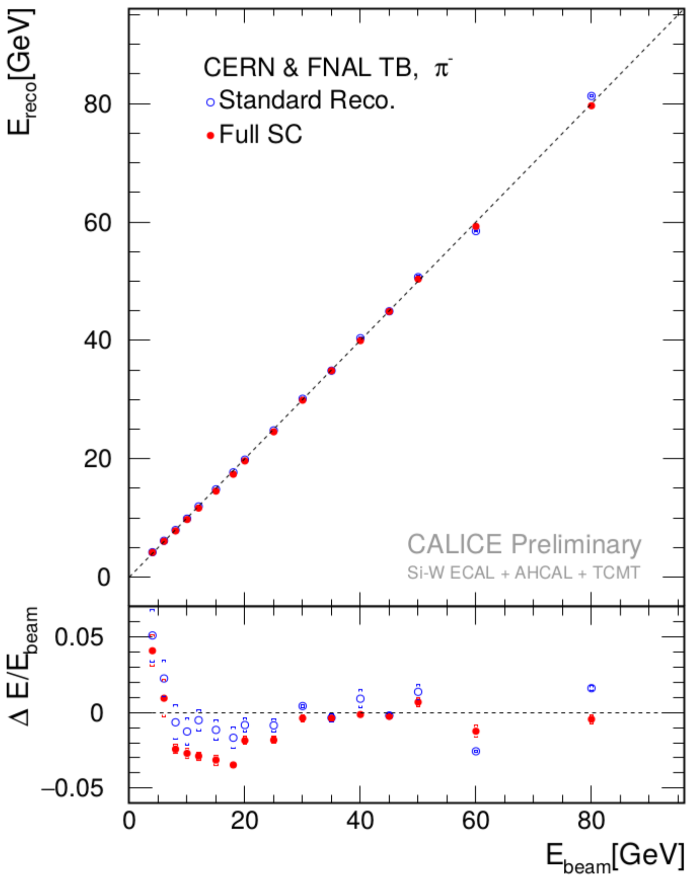


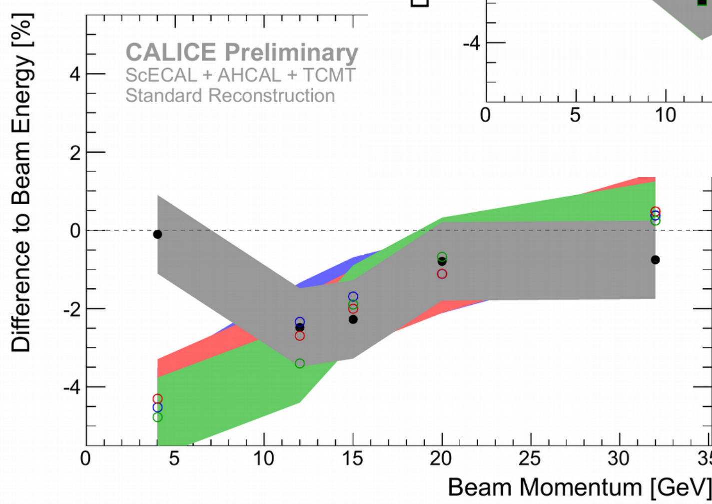


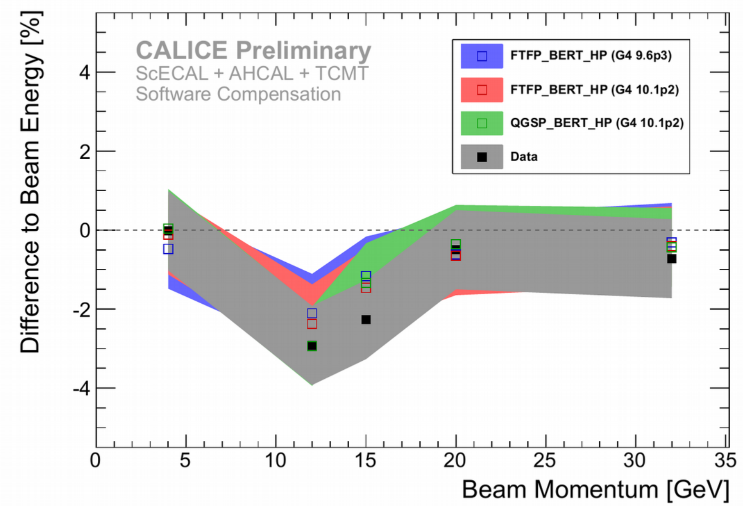
Response Linearity

> Good energy response reconstruction in all datasets

- ScECAL+AHCAL+TCMT: ≤4% deviation from linear response
- SiWECAL+AHCAL+TCMT: ≤5% deviation from linear response

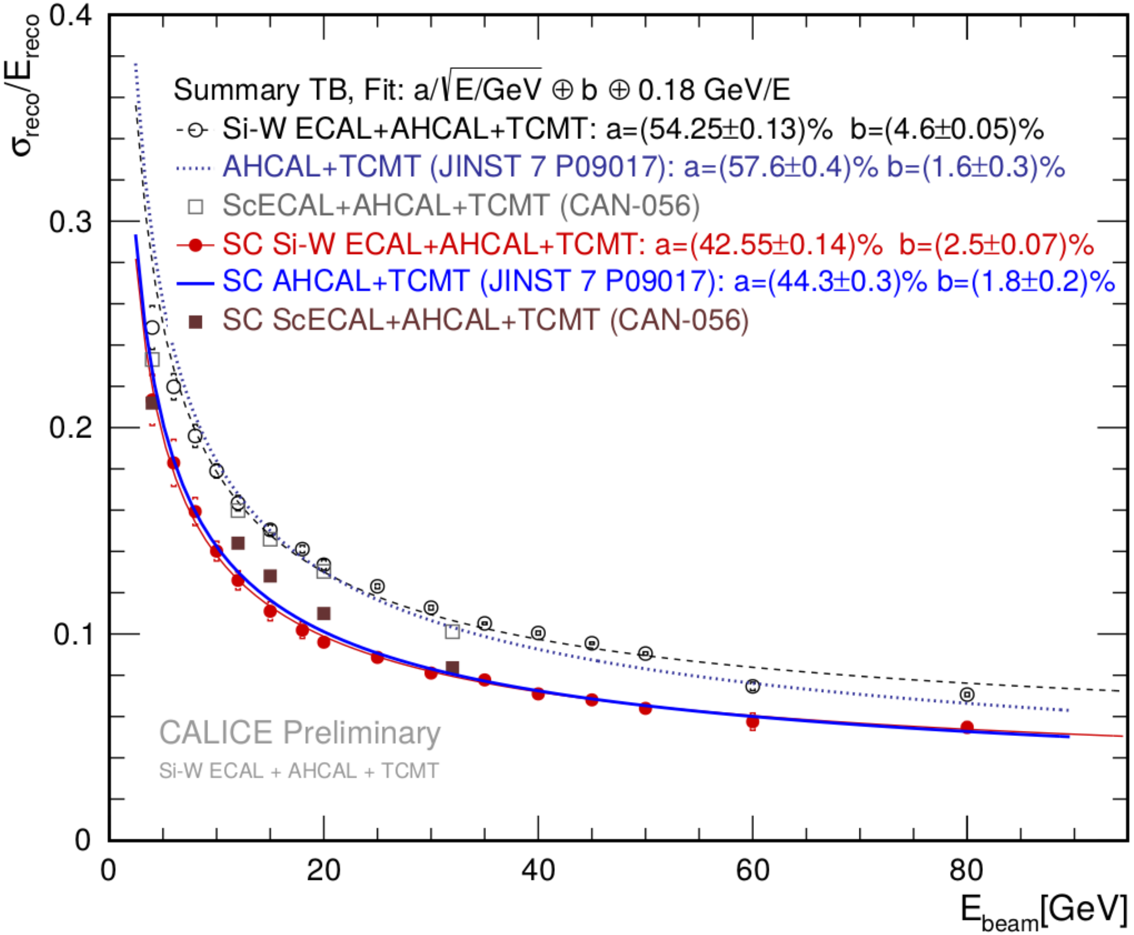






Energy Resolution

> Combined resolutions very close to AHCAL+TCMT reference analysis
  - Depsite different materials, sampling structure

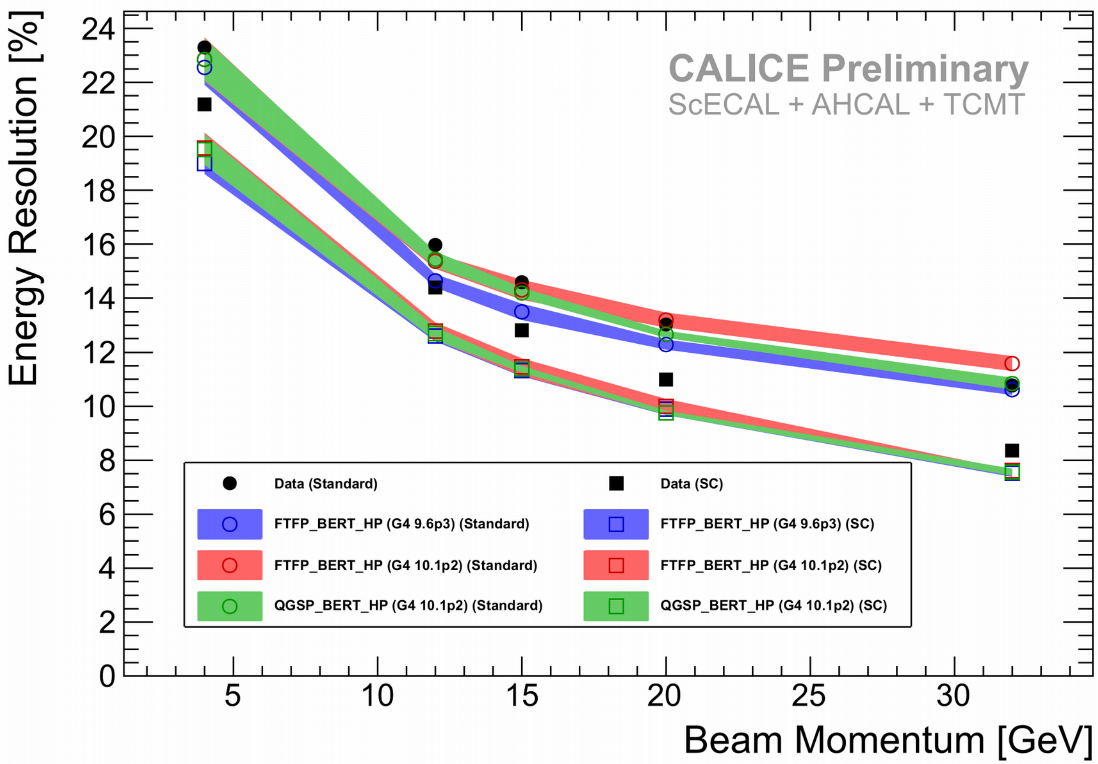


Energy Resolution

> Standard reconstruction: Very similar resolution in data and simulations

> Simulation overestimates SC improvement by 2% absolute

- Resolution improvement in data 10-20% relative
- Resolution improvement in simulation 15-30% relative

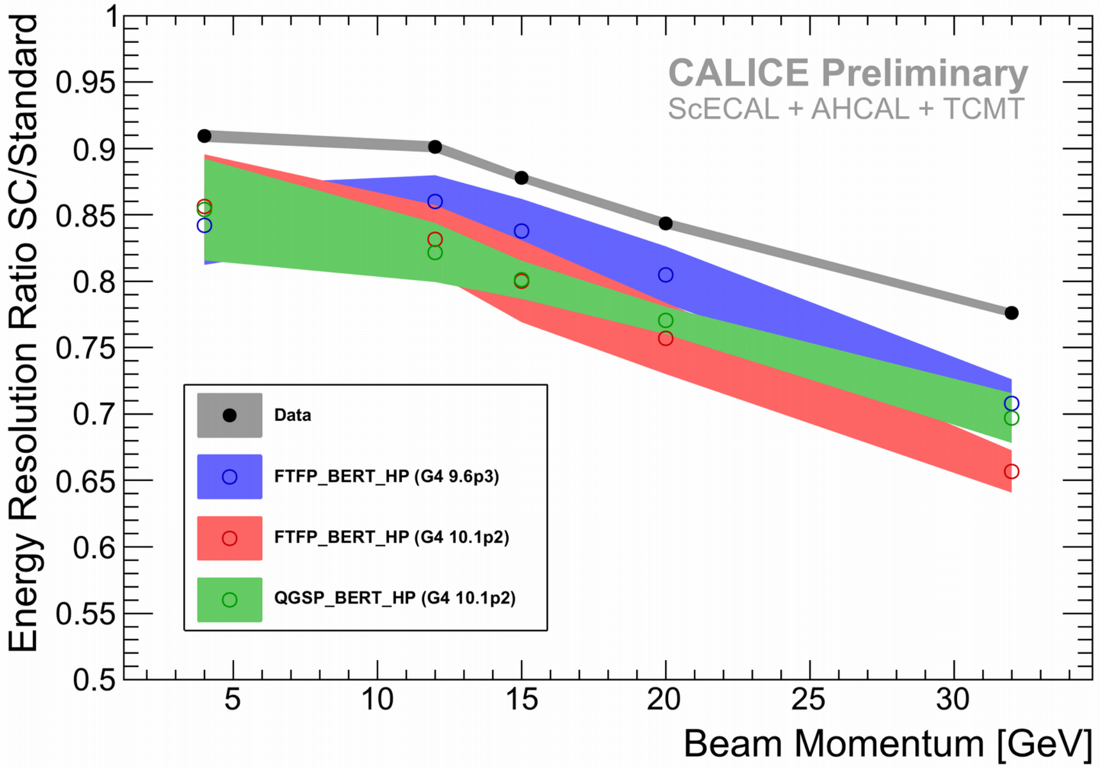


Energy Resolution – Software Compensation Improvement

> Standard reconstruction: Very similar resolution in data and simulations

> Simulation overestimates SC improvement by 2% absolute

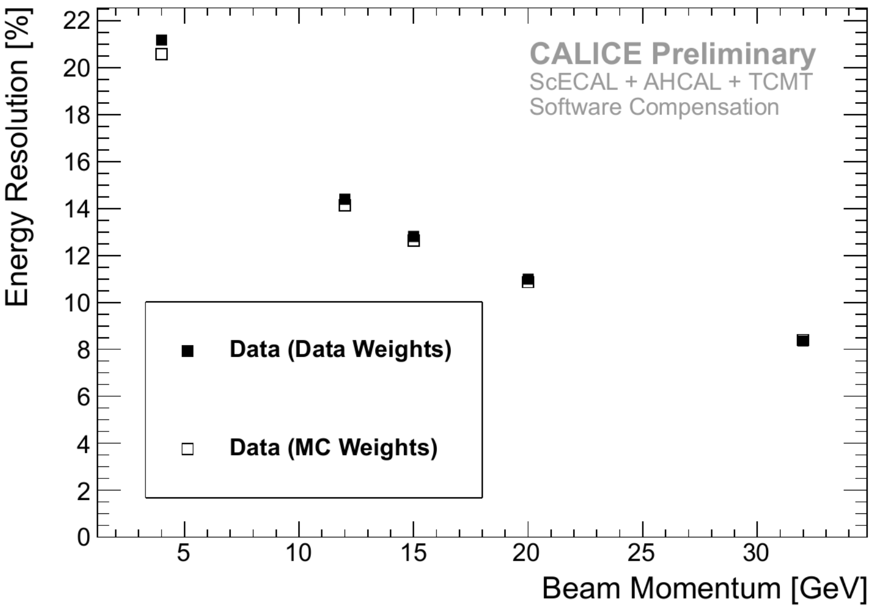
- Resolution improvement in data 10-20% relative
- Resolution improvement in simulation 15-30% relative

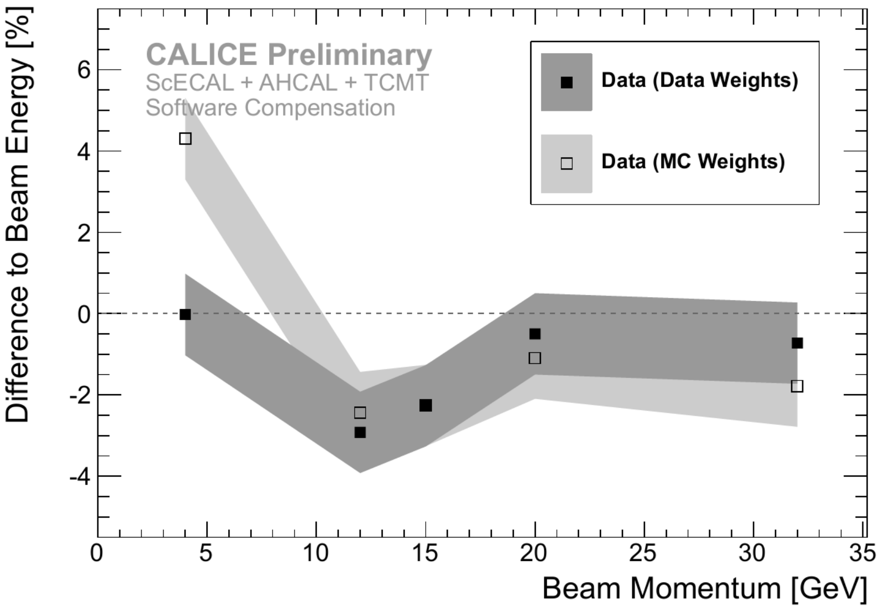


Applying SC Weights from Simulation to Data

- Slight degradation of response linearity (<4%)
- Slight improvement of energy resolution (<4% relative)

→ Can use SC weights from MC on data

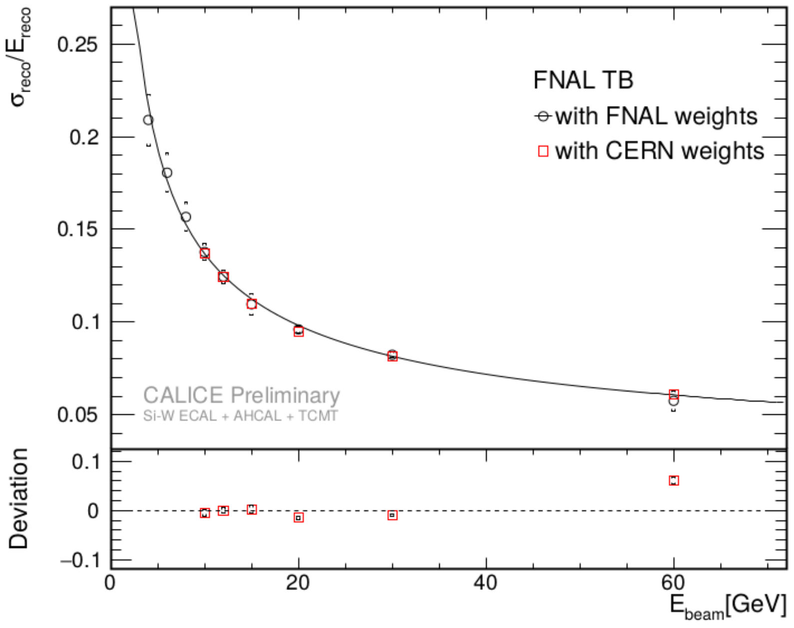


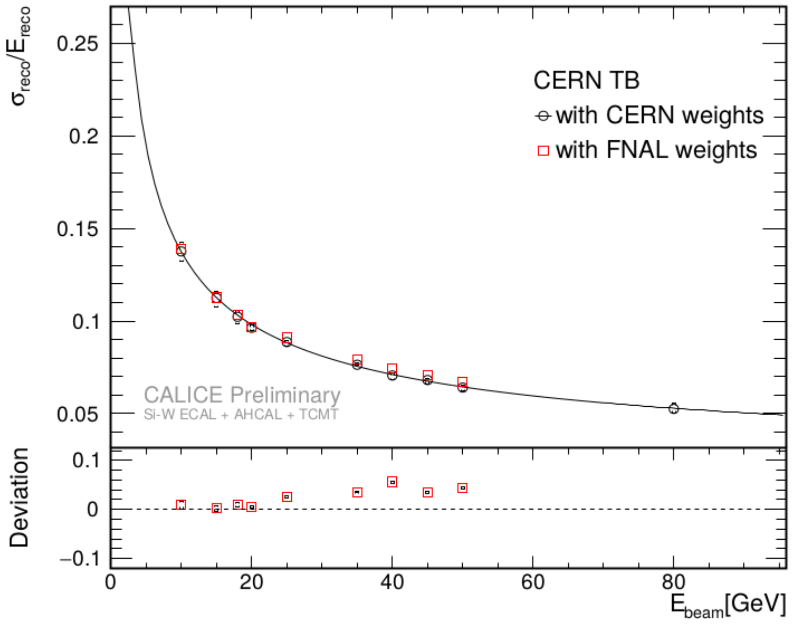


Applying SC Weights from Different Beam Periods

> Separate optimisation of SC weights for each set of testbeam data

> Cross-application of SC weights as systematic stability test





Summary

- Analyses of CALICE combined high granularity calorimeter systems
  - CAN-056 (ScECAL+AHCAL+TCMT), CAN-058 (SiWECAL+AHCAL+TCMT) (https://twiki.cern.ch/twiki/bin/view/CALICE/CaliceAnalysisNotes)
  - Journal papers in progress
- High granularity allows efficient selection of single particle events
  - Shower details well described by simulations
- Standard reconstruction energy resolutions well described in data/MC
- Improved energy resolution with software compensation reconstruction
- Energy resolution is the same with and without ScECAL

Backup

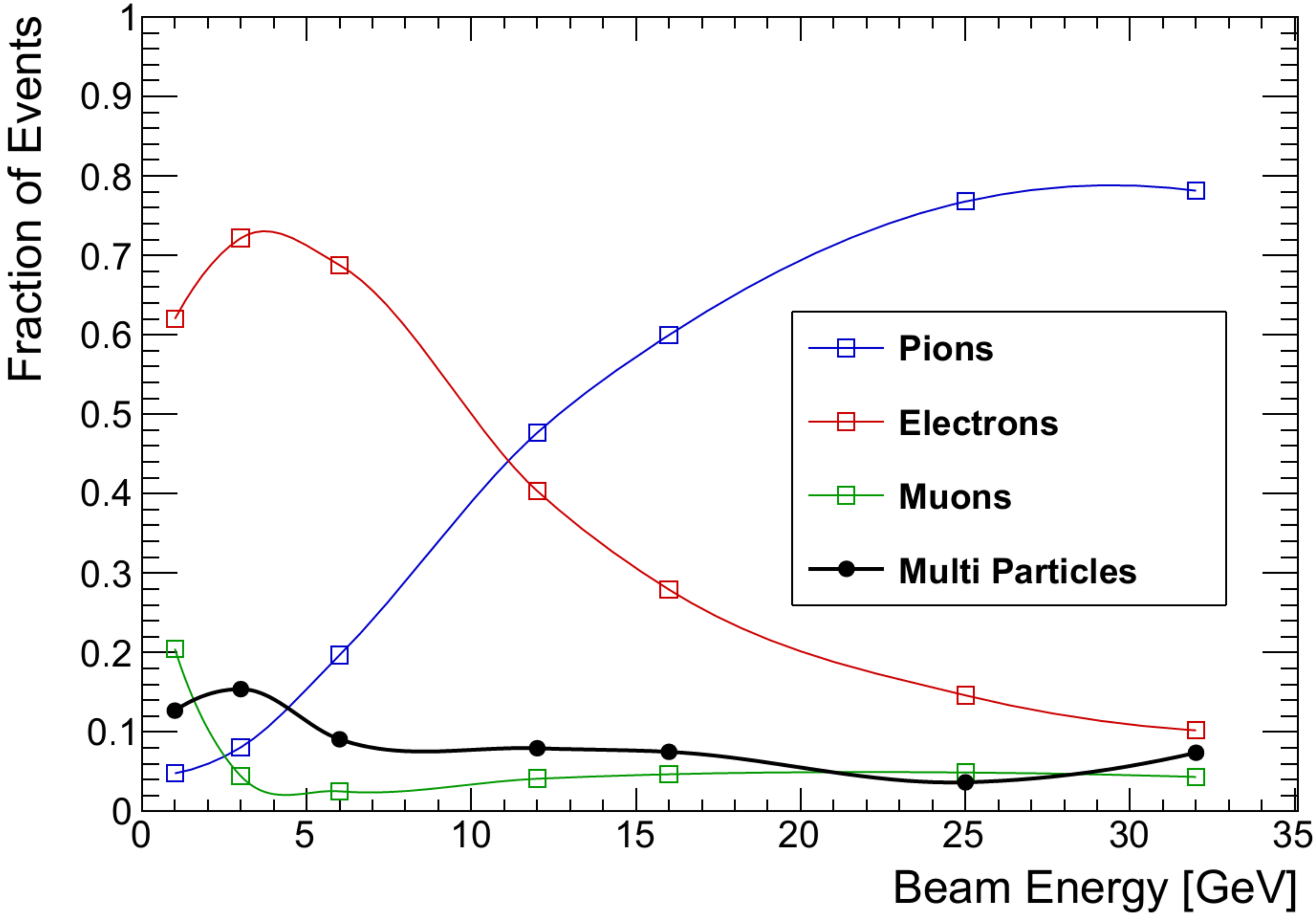
Pion Resolution Table

Run/Particle		Type	$(\sigma/\mu)_{\text{Std.}}$ [%]	$(\sigma/\mu)_{\text{SC}}$ [%]	$\frac{(\sigma/\mu)_{\text{SC}}}{(\sigma/\mu)_{\text{Std.}}}$
560506 (4 GeV)	π^-	Data	23.30 ± 0.08	21.19 ± 0.07	0.91 ± 0.00
	π^-	FTFP_BERT_HP	22.56 ± 0.65	19.00 ± 0.39	0.84 ± 0.03
	π^-	FTFP_BERT_HP$^{(*)}$	22.86 ± 0.81	19.57 ± 0.57	0.86 ± 0.04
	π^-	QGSP_BERT_HP	22.85 ± 0.78	19.51 ± 0.56	0.85 ± 0.04
560498 (12 GeV)	π^-	Data	15.98 ± 0.05	14.40 ± 0.05	0.90 ± 0.00
	π^-	FTFP_BERT_HP	14.65 ± 0.25	12.60 ± 0.20	0.86 ± 0.02
	π^-	FTFP_BERT_HP$^{(*)}$	15.38 ± 0.28	12.79 ± 0.32	0.83 ± 0.03
	π^-	QGSP_BERT_HP	15.45 ± 0.29	12.69 ± 0.25	0.82 ± 0.02
560496 (15 GeV)	π^-	Data	14.59 ± 0.04	12.81 ± 0.04	0.88 ± 0.00
	π^-	FTFP_BERT_HP	13.50 ± 0.30	11.31 ± 0.20	0.84 ± 0.02
	π^-	FTFP_BERT_HP$^{(*)}$	14.32 ± 0.37	11.45 ± 0.33	0.80 ± 0.03
	π^-	QGSP_BERT_HP	14.20 ± 0.20	11.38 ± 0.13	0.80 ± 0.01
560481 (20 GeV)	π^-	Data	13.03 ± 0.04	10.99 ± 0.04	0.84 ± 0.00
	π^-	FTFP_BERT_HP	12.29 ± 0.19	9.89 ± 0.22	0.80 ± 0.02
	π^-	FTFP_BERT_HP$^{(*)}$	13.19 ± 0.28	9.99 ± 0.28	0.76 ± 0.03
	π^-	QGSP_BERT_HP	12.67 ± 0.13	9.76 ± 0.08	0.77 ± 0.01
560474 (32 GeV)	π^-	Data	10.77 ± 0.03	8.36 ± 0.02	0.78 ± 0.00
	π^-	FTFP_BERT_HP	10.62 ± 0.20	7.52 ± 0.13	0.71 ± 0.02
	π^-	FTFP_BERT_HP$^{(*)}$	11.59 ± 0.28	7.61 ± 0.03	0.66 ± 0.02
	π^-	QGSP_BERT_HP	10.84 ± 0.22	7.56 ± 0.13	0.70 ± 0.02

Pion Selection Efficiencies and Biases

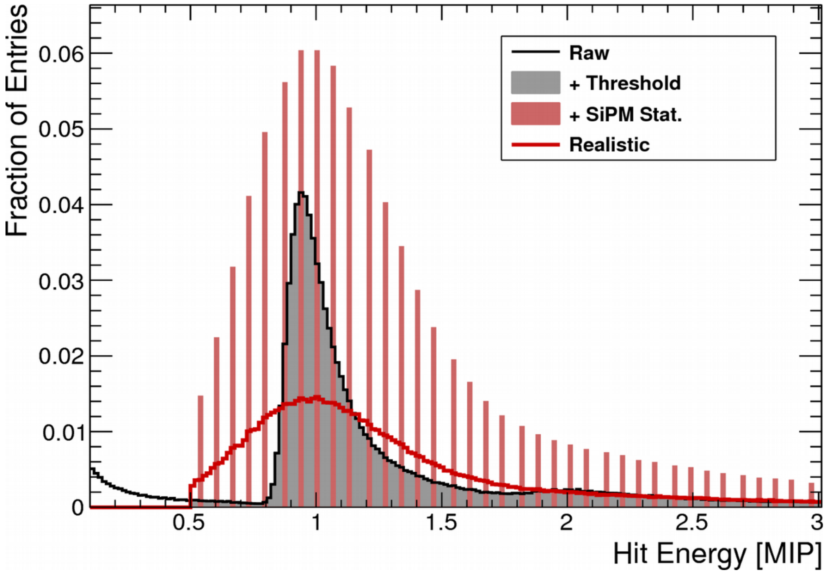
Run/Particle		Physics List	$\mu_{\text{FHI}}/\text{GeV}$	$\sigma_{\text{FHI}}/\mu_{\text{FHI}}$	$\mu_{\text{sel.}}/\text{GeV}$	$\sigma_{\text{sel.}}/\mu_{\text{sel.}}$	$\epsilon_{\text{sel.}}$
560506 (4 GeV)	π^-	FTFP_BERT_HP	3.82	22.92%	3.83	22.86%	46.1%
	π^-	FTFP_BERT_HP(*)	3.81	22.64%	3.82	22.59%	46.5%
	π^-	QGSP_BERT_HP	3.80	22.95%	3.81	22.87%	45.9%
	e^-	QGSP_BERT	-	-	-	-	0.2%
560498 (12 GeV)	π^-	FTFP_BERT_HP	11.62	15.49%	11.67	15.37%	49.5%
	π^-	FTFP_BERT_HP(*)	11.68	14.73%	11.71	14.65%	49.6%
	π^-	QGSP_BERT_HP	11.54	15.54%	11.59	15.45%	49.4%
	e^-	QGSP_BERT	-	-	-	-	<0.1%
560496 (15 GeV)	π^-	FTFP_BERT_HP	14.64	14.43%	14.70	14.30%	48.8%
	π^-	FTFP_BERT_HP(*)	14.69	13.59%	14.74	13.49%	49.1%
	π^-	QGSP_BERT_HP	14.66	14.30%	14.71	14.20%	49.2%
	e^-	QGSP_BERT	-	-	-	-	<0.1%
560481 (20 GeV)	π^-	FTFP_BERT_HP	19.69	13.25%	19.78	13.19%	47.5%
	π^-	FTFP_BERT_HP(*)	19.70	12.35%	19.77	12.28%	47.6%
	π^-	QGSP_BERT_HP	19.78	12.74%	19.86	12.66%	48.0%
	e^-	QGSP_BERT	-	-	-	-	<0.1%
560474 (32 GeV)	π^-	FTFP_BERT_HP	31.97	11.59%	32.15	11.58%	44.3%
	π^-	FTFP_BERT_HP(*)	31.97	10.66%	32.12	10.60%	44.3%
	π^-	QGSP_BERT_HP	31.92	10.96%	32.08	10.82%	45.0%
	e^-	QGSP_BERT	-	-	-	-	<0.1%

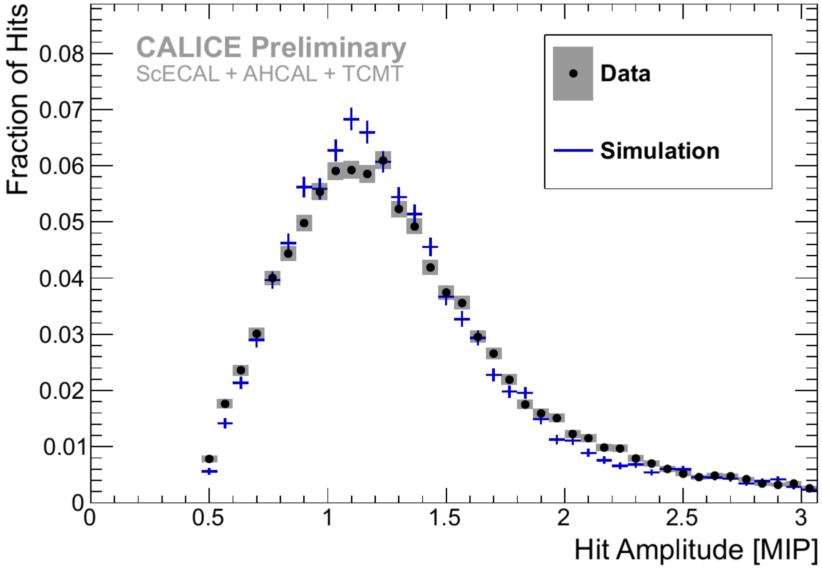
Approximate FNAL Beam Composition



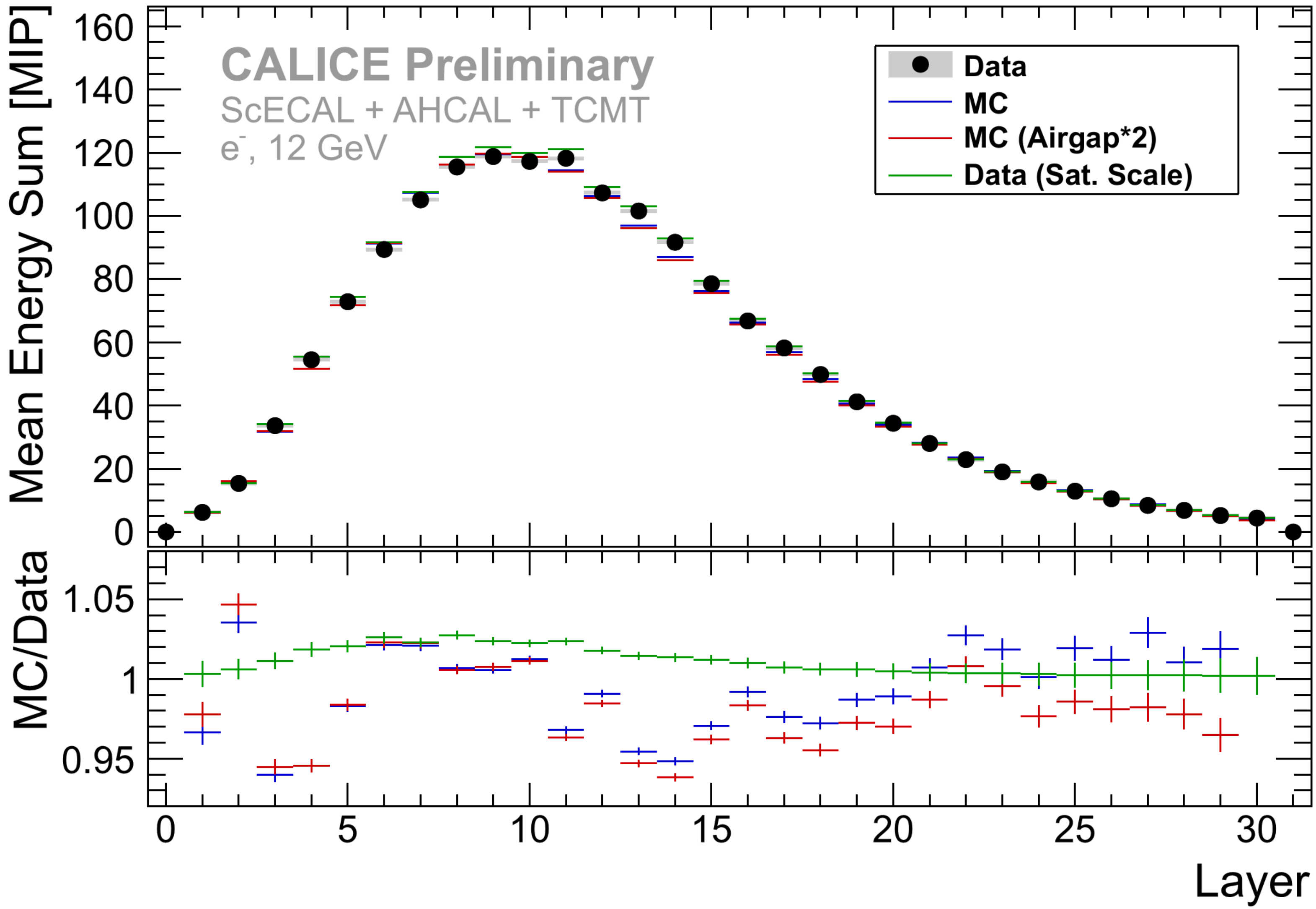
Sensor Digitisation Effects

> Notable effect of SiPM modelling on MIP spectrum
  - Electronics noise smears out quantisation
> Good agreement with data





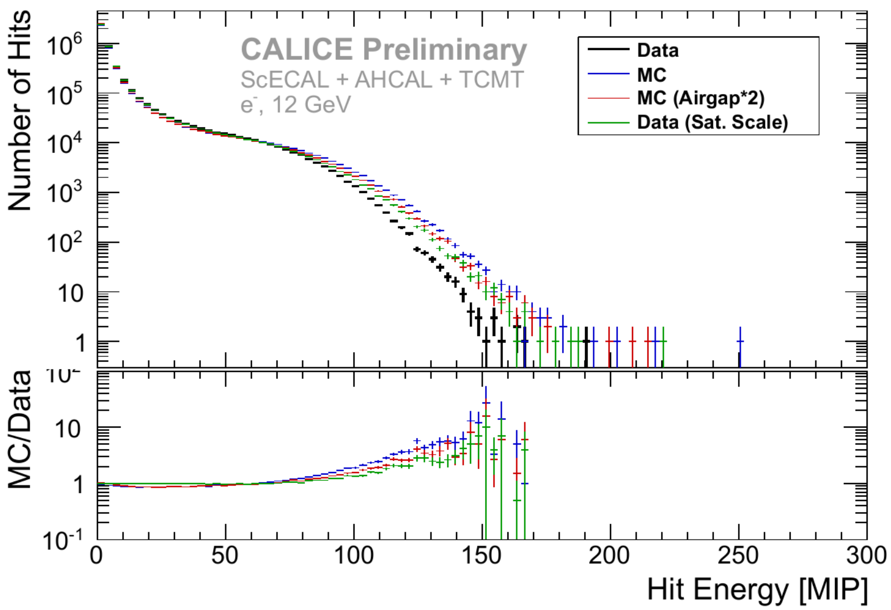
Electron Data/MC: Longitudinal Shower Profile

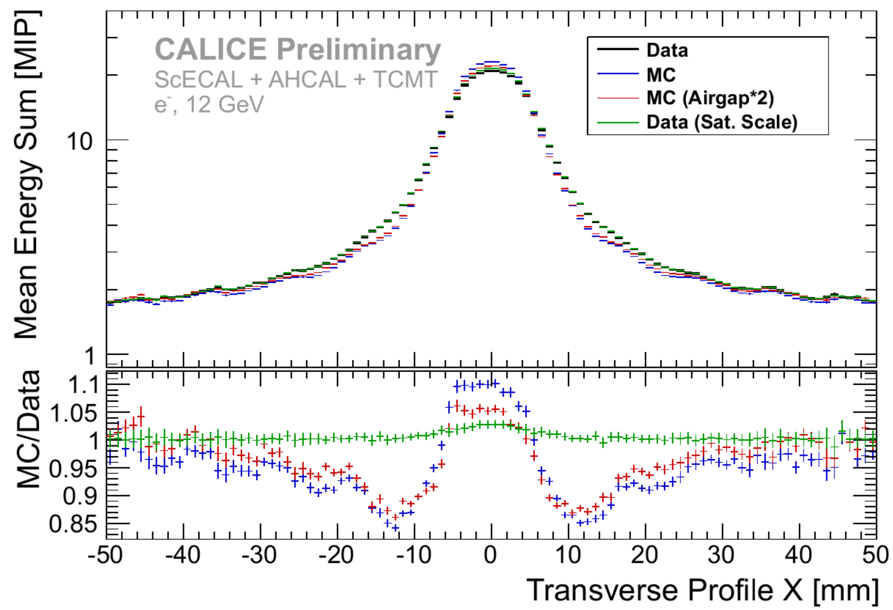


Electron Data/MC: Hit Energy, Transverse Shower Profile

> Slight overestimation of hit energy tails and transverse shower profile in electron MC

- Irrelevant for energy sum
- Not explained by SiPM saturation effects
- Not explained by geometry mismodelling



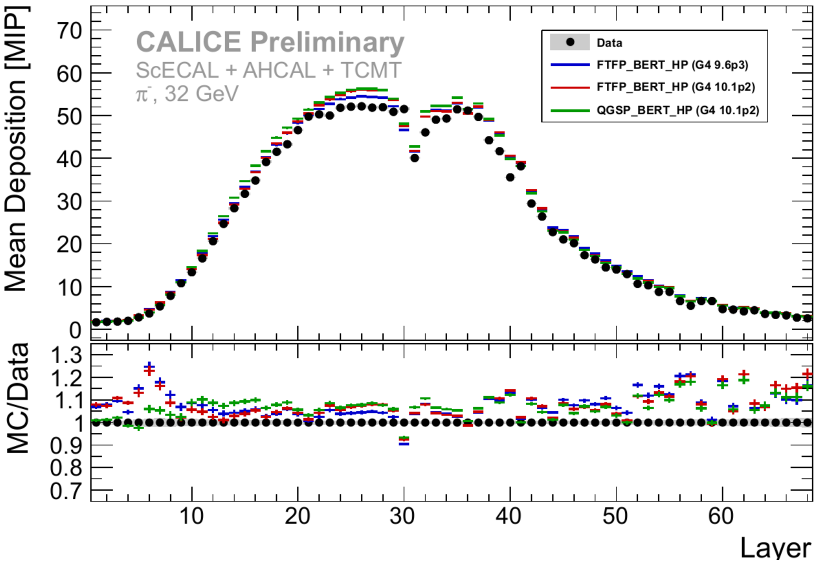


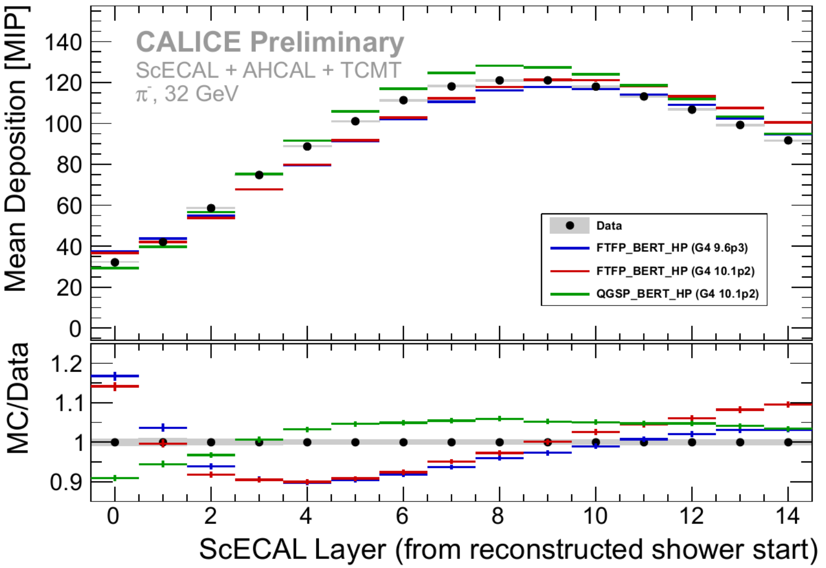
Simulation Comparison – Shower Profiles

> Full Geant4 detector simulation
  - Detailed geometry, materials
  - Realistic digitisation of sensor effects

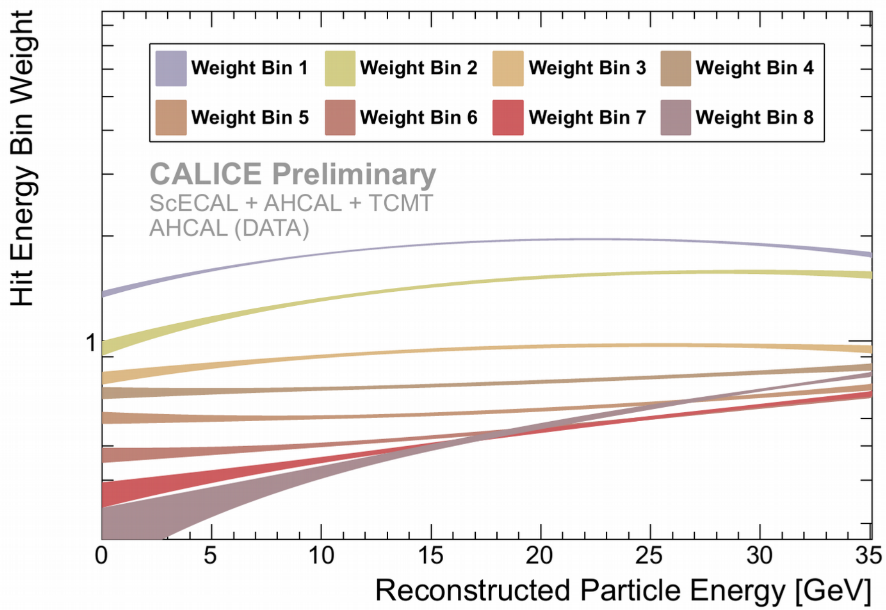
> Longitudinal pion shower profile in good agreement with simulations
  - ~5% excess depositions in MC

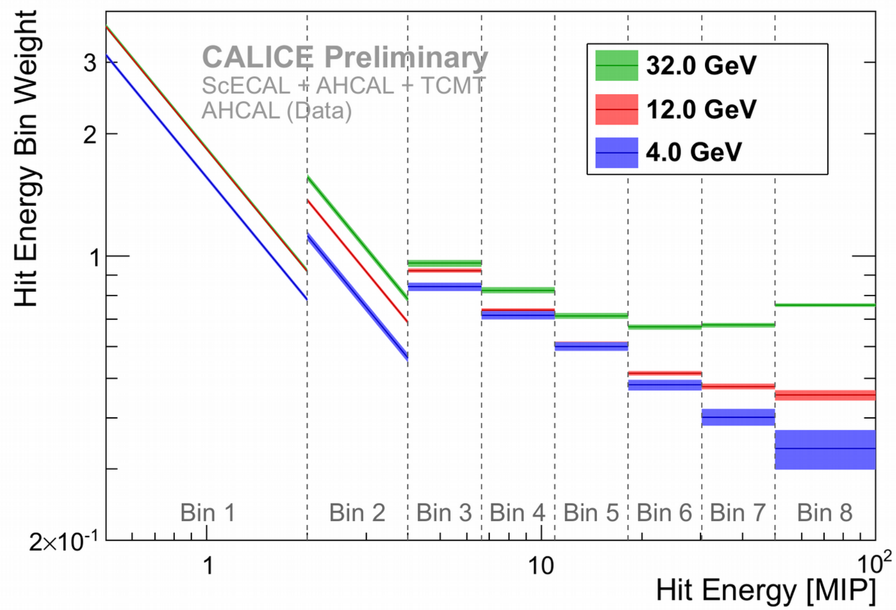
> Physics modelling uncertainties in ScECAL shower profile from FHI
  - Physics lists show different behaviours
  - Data between physics lists



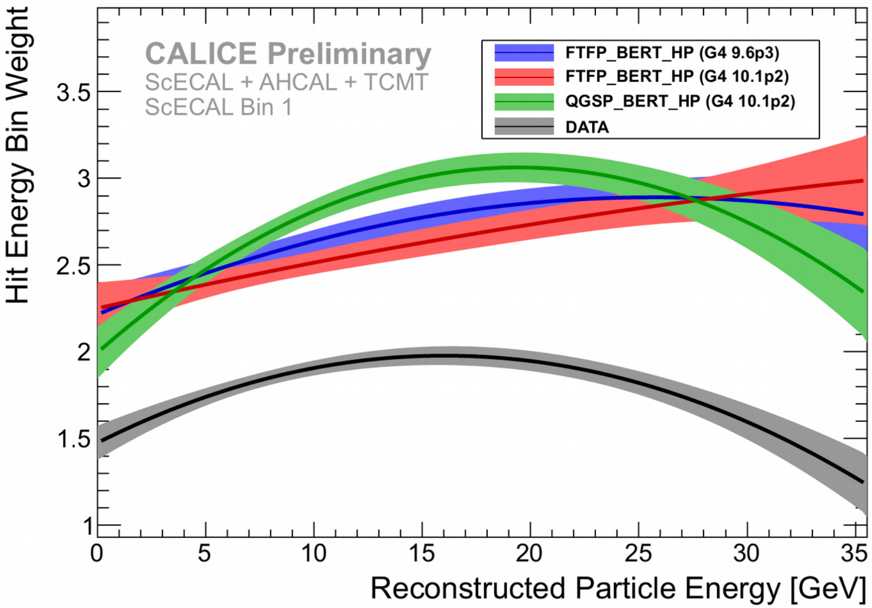


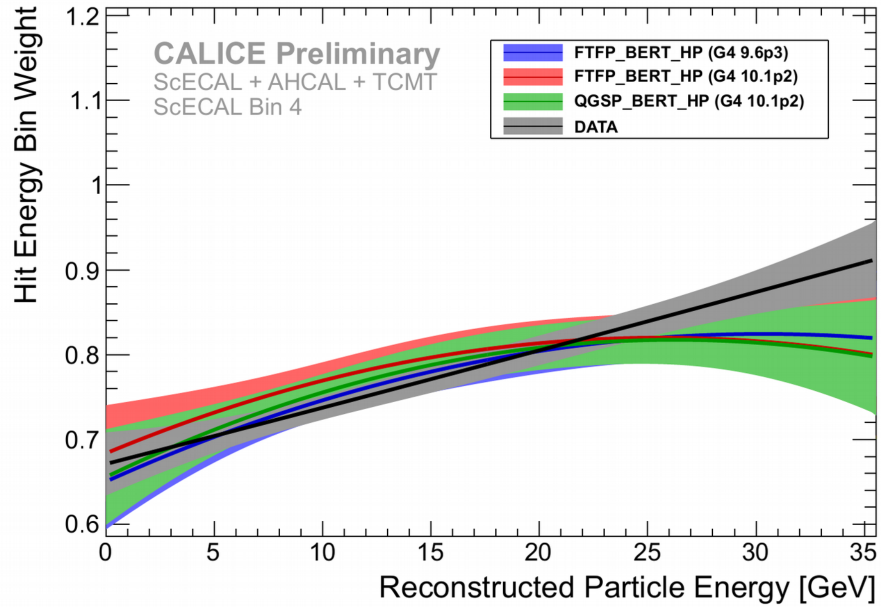
SC Weights AHCAL (Data)

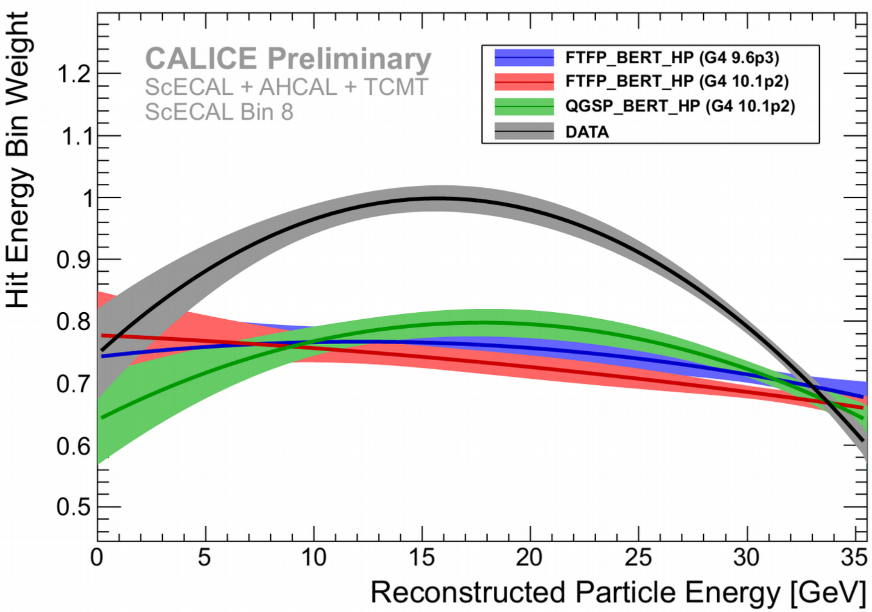


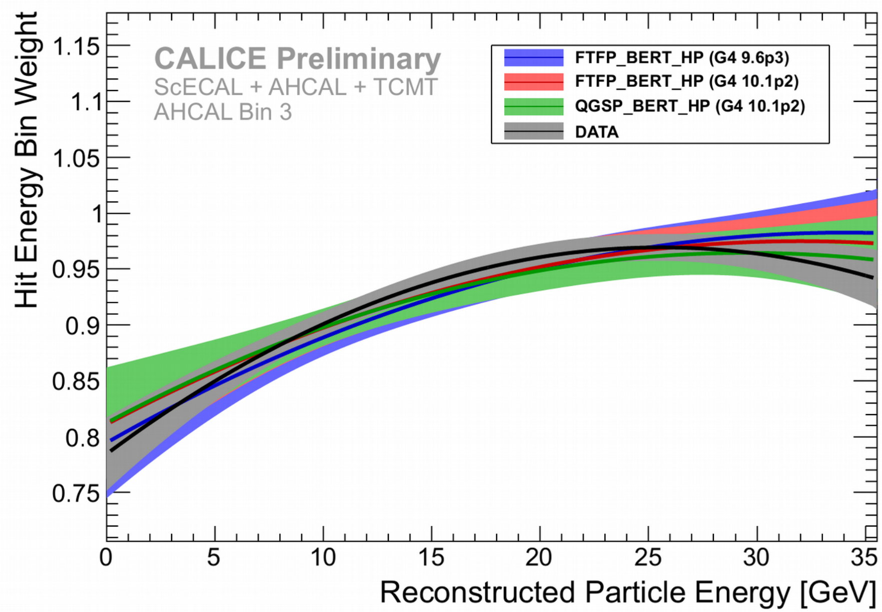


SC Weights Data vs. MC



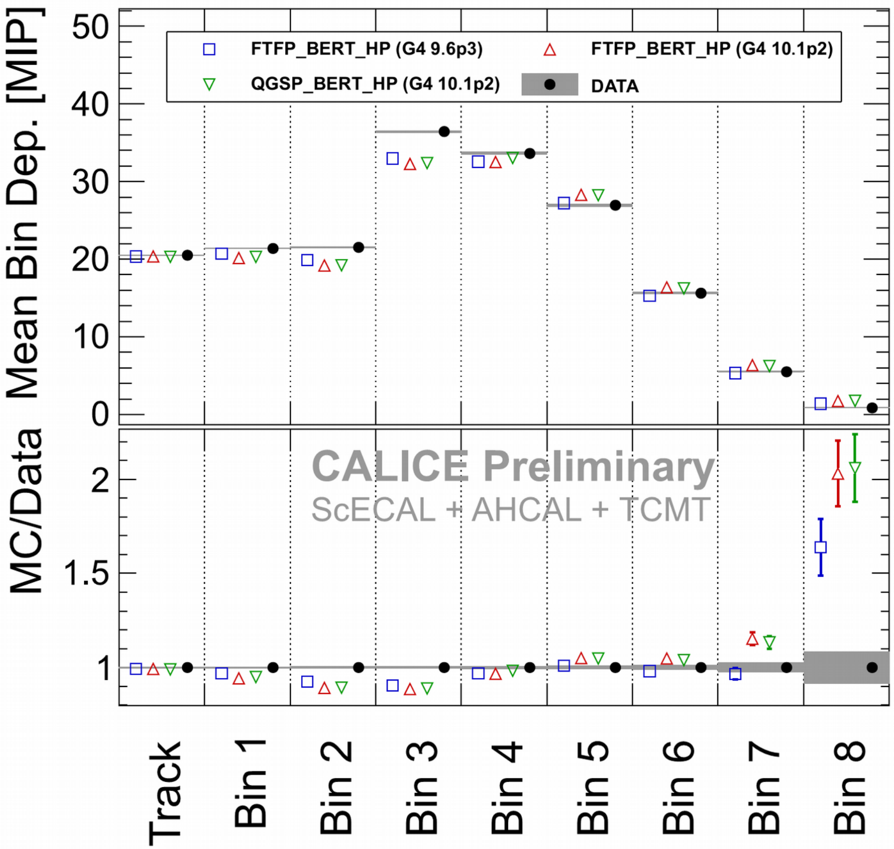




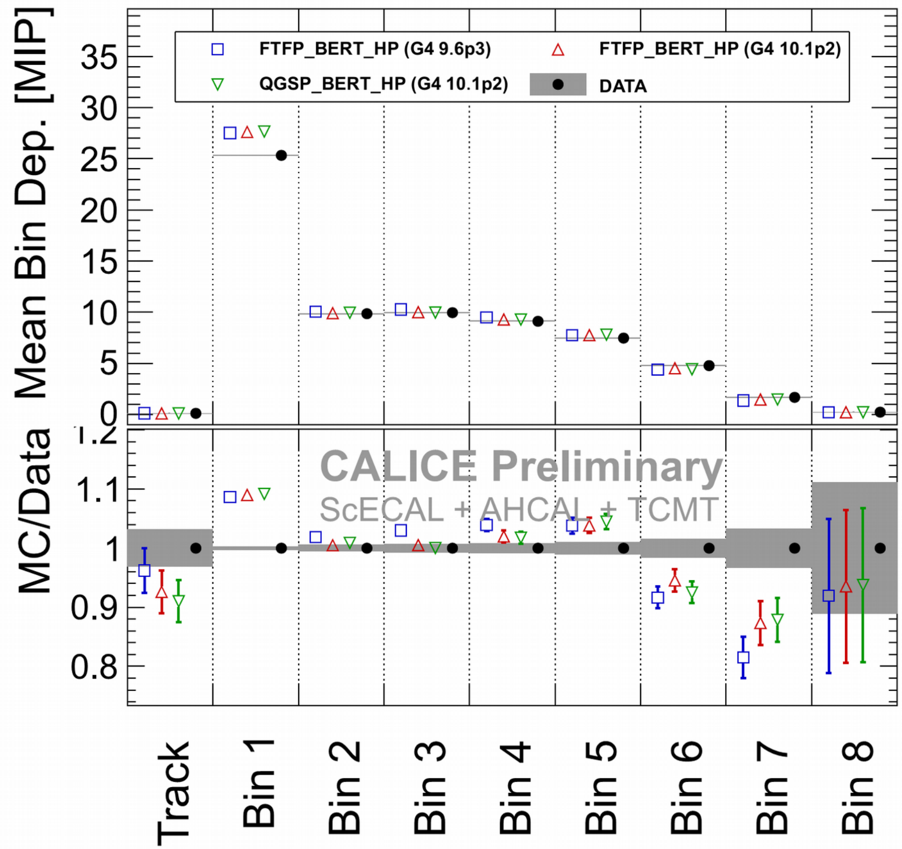


Mean SC Bin Deposition Sum (4GeV)

ScECAL

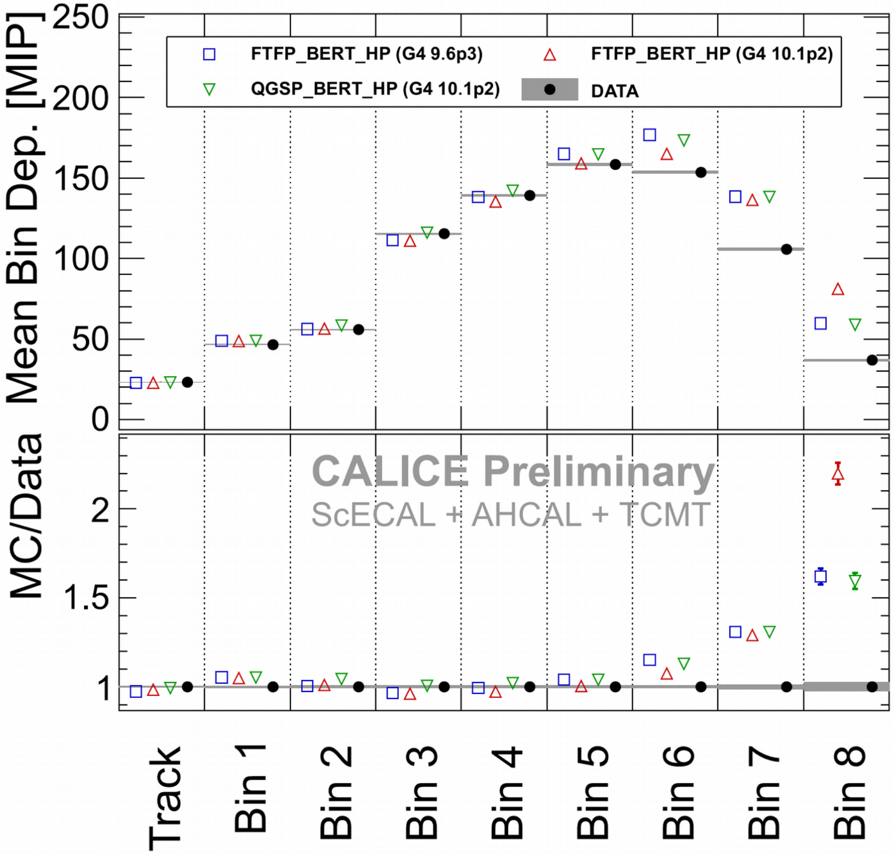


AHCAL

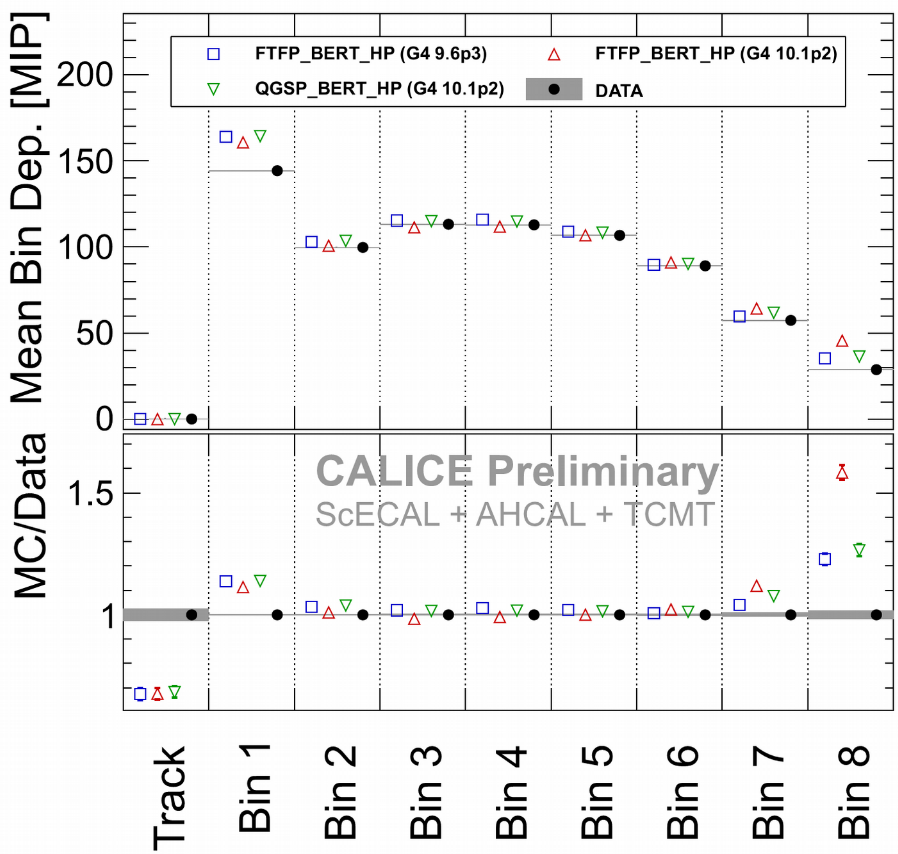


Mean SC Bin Deposition Sum (32GeV)

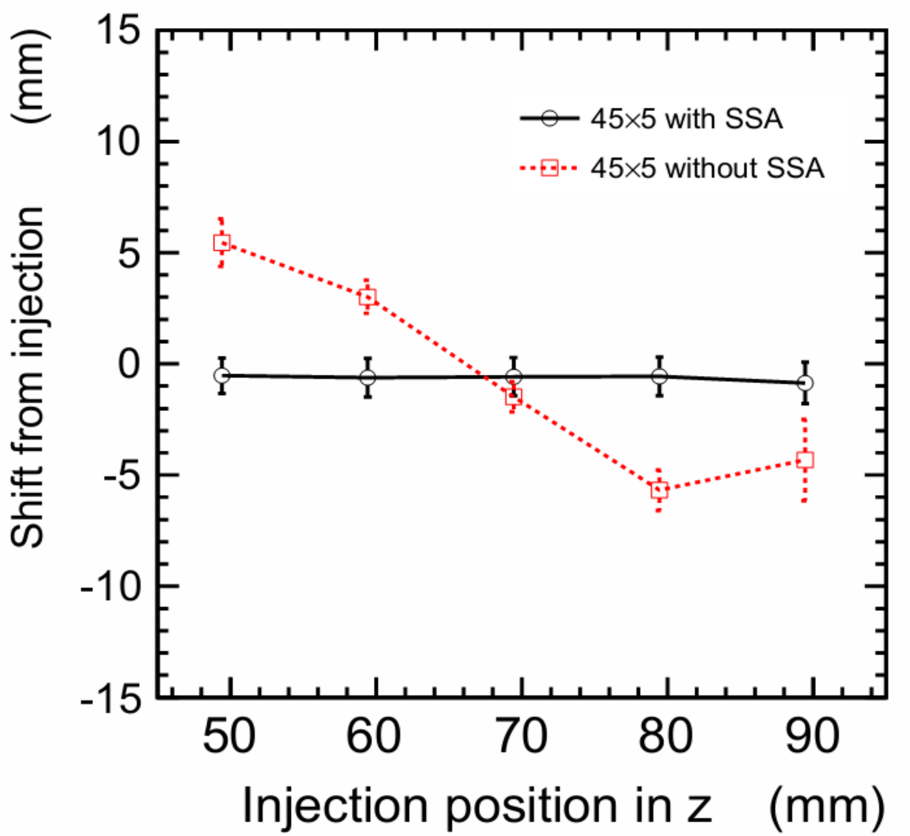
ScECAL

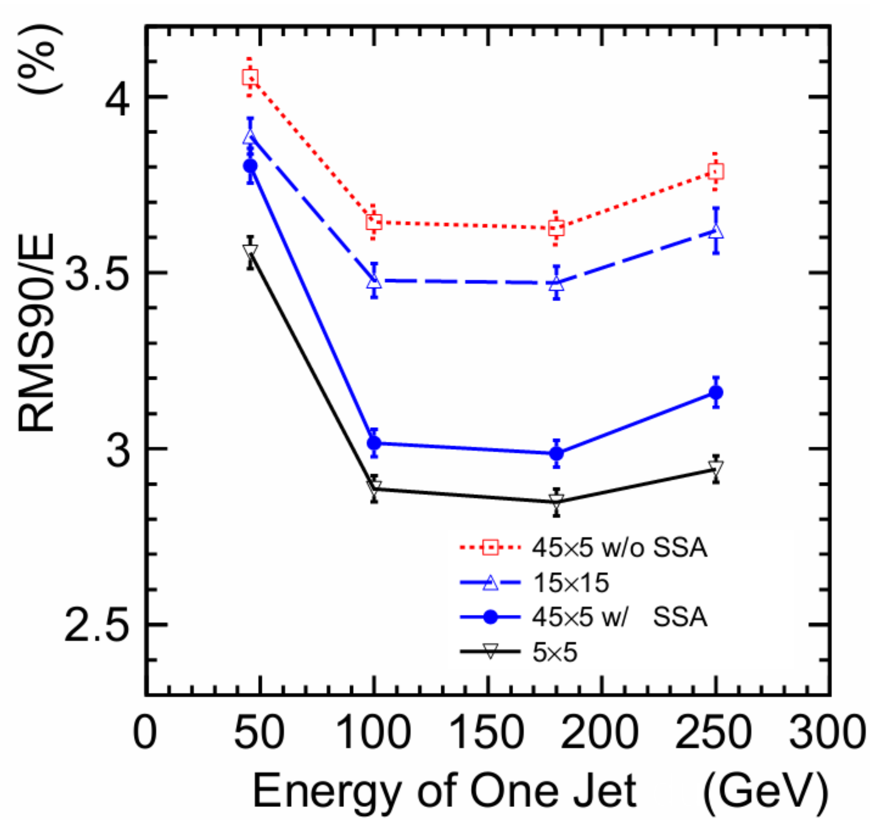


AHCAL



PFA Performance in ScECAL Strip Geometry





"A novel strip energy splitting algorithm for the fine granular readout of a scintillator strip electromagnetic calorimeter"
Katsushige Kotera et. al.
(NIM A789, arXiv: 1405.4456)