Shower Characteristics of Particles with Momenta up to 100 GeV in the CALICE Scintillator-Tungsten HCAL

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and the CLICdp collaboration

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Hadron Calorimeter at multi-TeV CLIC

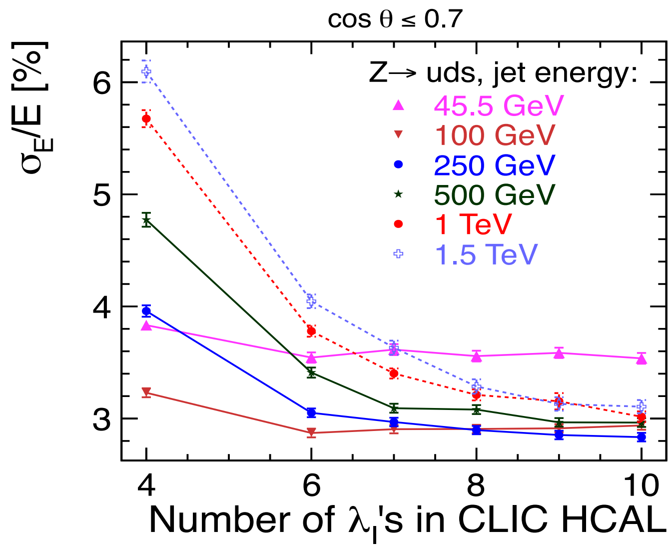
Requirements:

- Jet energy resolution 5-3.5% for 50 GeV -1 TeV jets (separate Z and W)
- Deep calorimeter to contain high energy showers
- Compact calorimeter inside solenoid

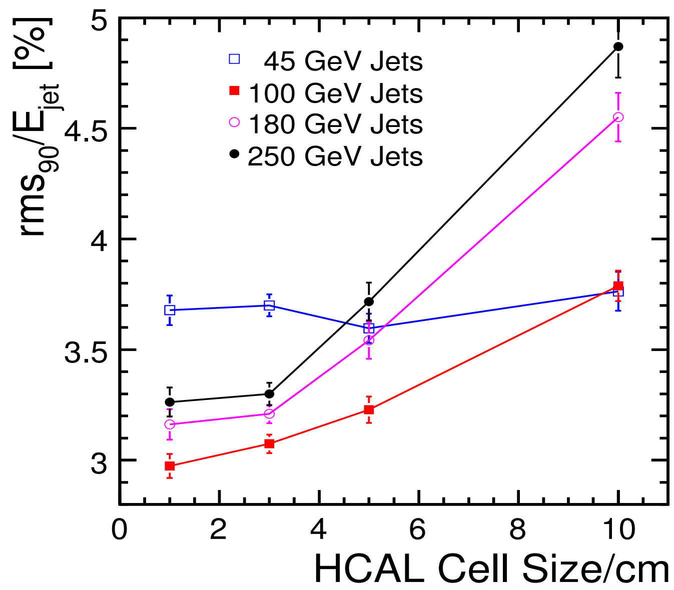
Possible solution:

- Dense absorber material i.e. tungsten for the barrel HCAL
- Particle flow analysis:
  - Identify individual particles in each jet
  - Match tracks with calorimeter clusters
  - Reconstruct jet energy:
    - Momentum of charged particles (60%)in tracker $\sigma(p_T)/p_T^2 \sim 2 \cdot 10^{-5}\ \mathrm{GeV}^{-1}$
    - Enery of photons (30%) in ECAL $\sigma/E \leq 20\%/\sqrt{E}$
    - energy of neutral hadrons(10%) in HCAL $\sigma(E)/E > 50\% / \sqrt{E(\mathrm{GeV})}$

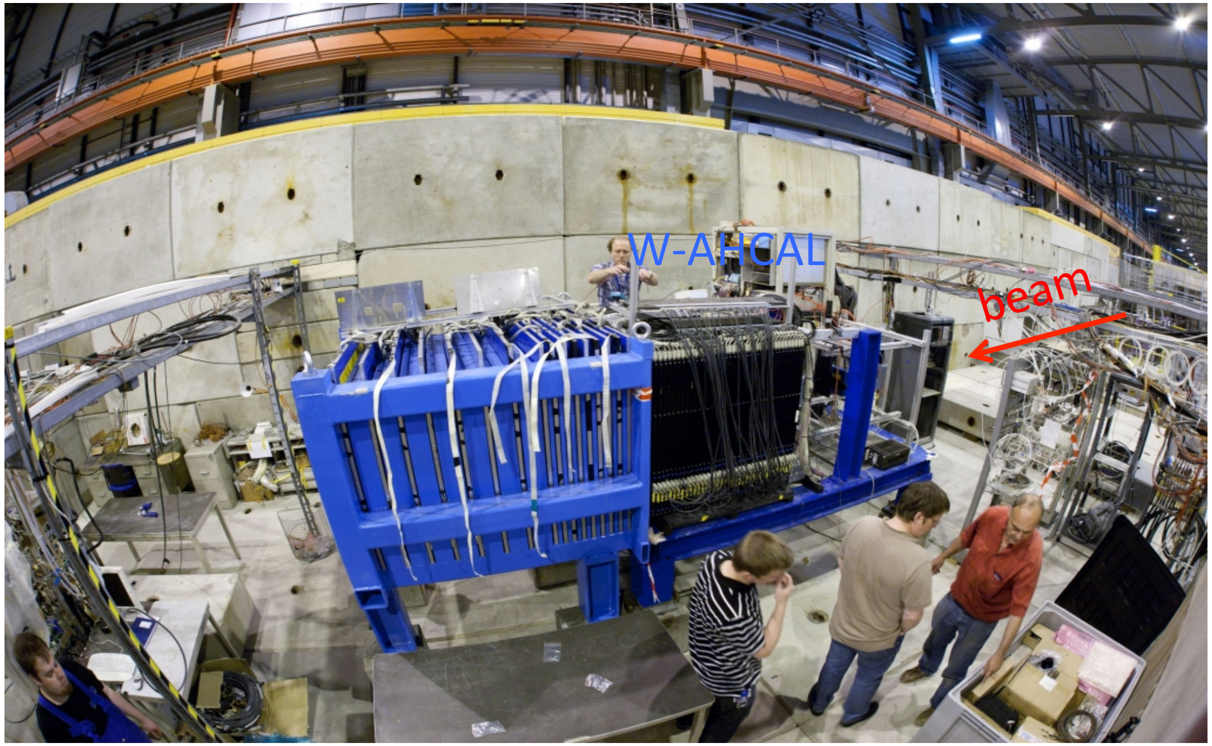
=> Need highly granular and compact calorimeters

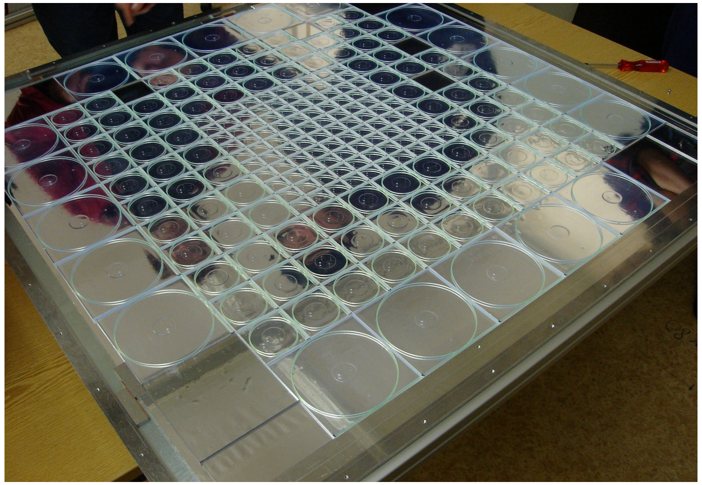


(From CLIC CDR, CERN-2012-003)

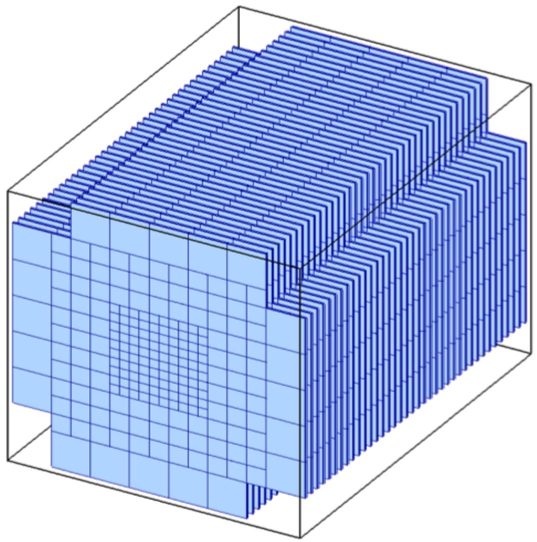


CALICE W-AHCAL Prototpye





Scintillator layer



Full prototype

- Sandwich calorimeter:
  1cm thick W absorber plates interleaved with 0.5cm thick scintillator tiles
- Granularity: 3 x 3 cm^2 tiles in central region, surrounded by 6 x 6 cm^2 and 12 x 12 cm^2 tiles
- Analogue readout: wavelength shifting fibers connected to Silicon Photomultipliers (SiPM)

Two Measurement Campaigns at CERN PS and SPS

2010 at CERN PS beam line T9

- 1 GeV ≤ p_{beam} ≤ 10 GeV
- Beam composition: $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, p
- Beam line equipped with 2 threshold Cherenkov counters filled with CO_2, 0 ≤ p ≤ 3.5 bar
- W-AHCAL consisting of 30 layers corresponding to 3.9 λ_I or 85 X_0

Publication : JINST 9 (2014) 01004 (http://iopscience.iop.org/1748-0221/9/01/P01004/pdf/1748-0221_9_01_P01004.pdf)
comparison to Geant4 version 9.6.p02

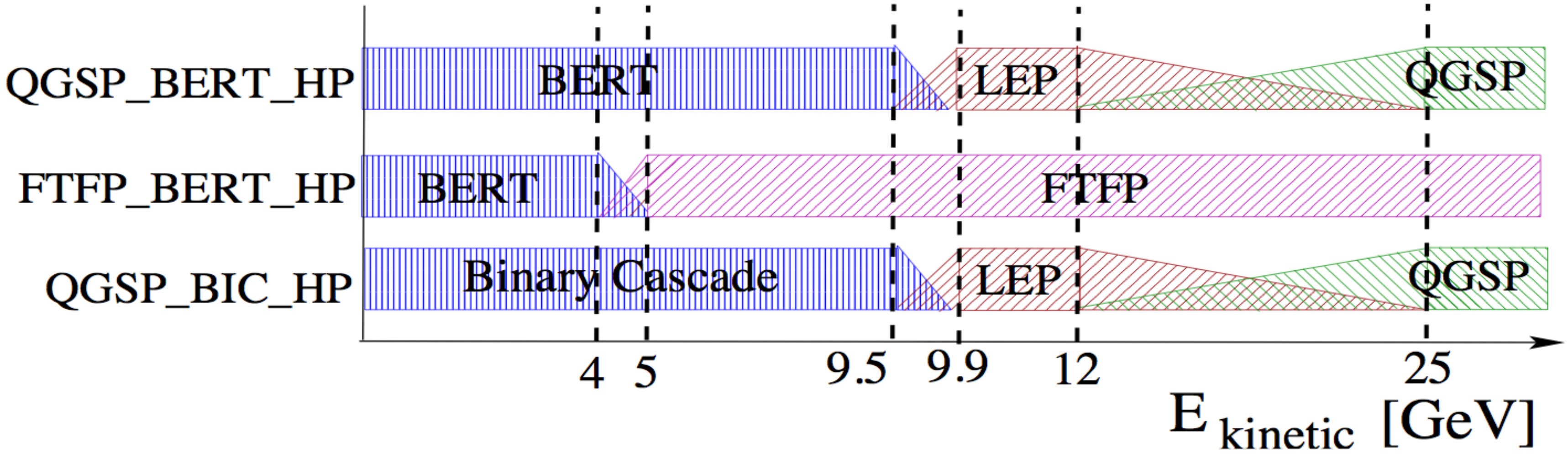
2011 at CERN SPS beam line H8

- 10 GeV ≤ p_{beam} ≤ 300 GeV
- Beam composition: $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, p
- Target choice: $e^{\pm}$ - beam versus hadron beam
- Beam line equipped with 2 threshold Cherenkov counters filled with He, 0 ≤ p ≤ 3 bar
- Dedicated $\mu^{\pm}$ beams (Fe dump upstream of experiment) for calibration
- W-AHCAL consisting of 38 layers corresponding to 4.9 λ_I or 108 X_0
- Tail catcher not (yet) used for data analysis

CALICE Note CAN-044 (https://twiki.cern.ch/twiki/pub/CALICE/CaliceAnalysisNotes/CAN-044.pdf)
comparison to Geant4 version 9.5.p01

GEANT4 Simulations

- Comparison of experimental data with GEANT4 simulations
- Experimental setup and read out electronics modeled as detailed as possible
  Test of modeled setup with electro magnetic showers
- Various physics models are combined to physics lists



Tungsten produces a considerable amount of spallation neutrons

=> Use in addition the data driven high precision neutron package (HP) to transport neutrons below 20 MeV down to thermal energies

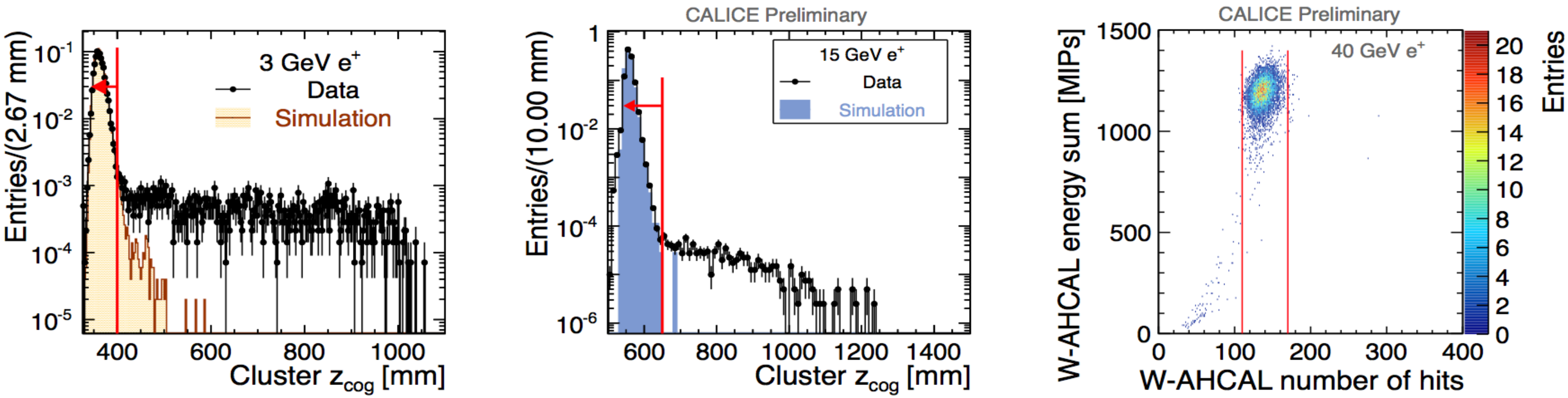
Electron Selection

PS+ SPS data:

- Pre selection with Cherenkov Counter
- Cut on center of gravity of shower depth

SPS data

- Dedicated $e^{\pm}$ runs
- One cluster and no tracks in event
- Number of hits within given range = $f(p_{beam})$

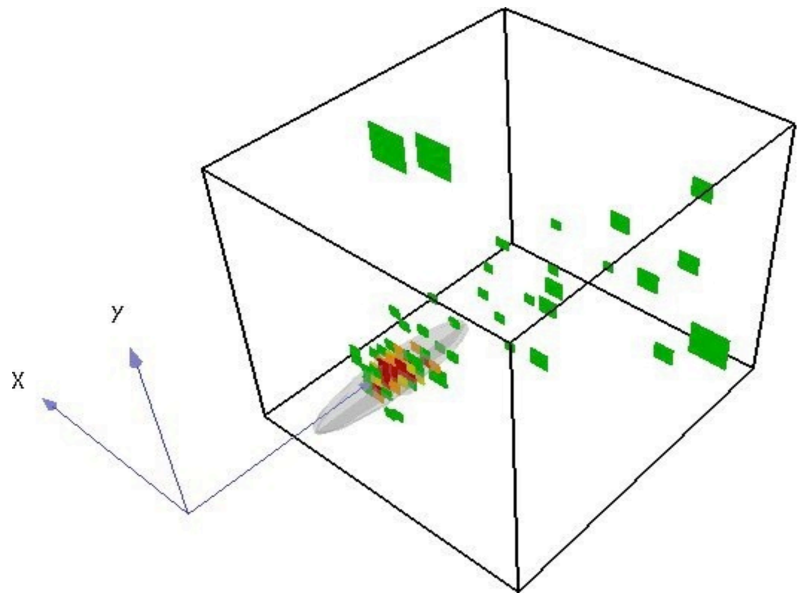


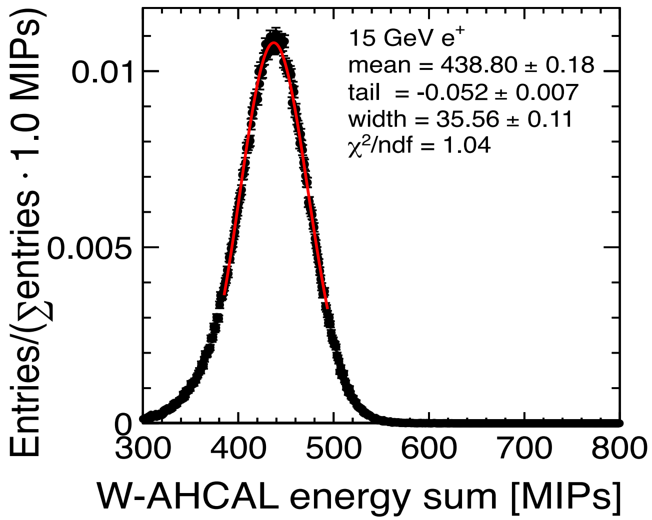
Electron Signal in W-HACAL

One W-AHCAL absorber layer: 1cm W ≈ 2.8 X_0
⇒ $e^{\pm}$ shower very dense and compact

For energy evaluation consider only signals in first 20 layers of central 3 x 3 cm^2 tiles
⇒ reduction in noise

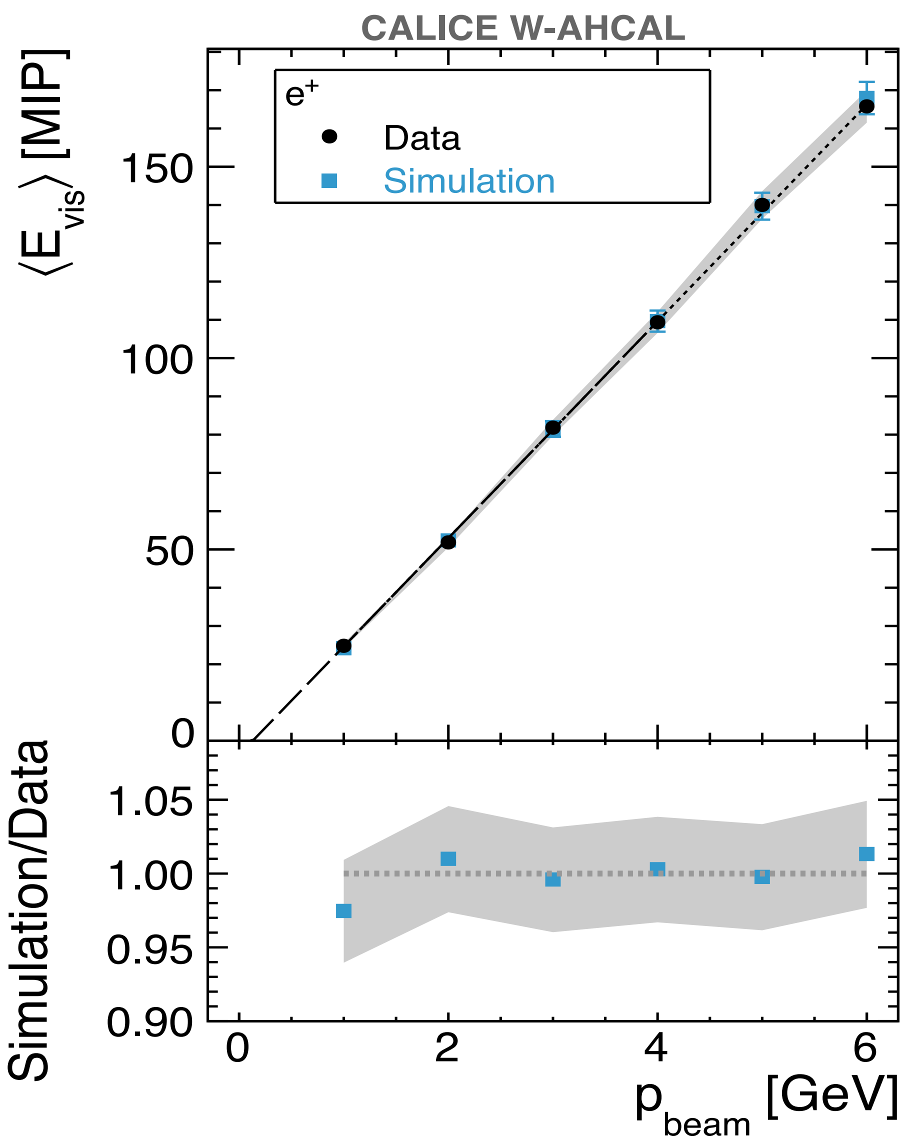
Measurements performed in units of MIP signal (from calibration runs with μ)





Line shape slightly asymmetric:
Fit signal with Novosibirsk function within ±1.5 σ
(Gaussian with a tail)

e^+ Linearity at PS (1-6 GeV)

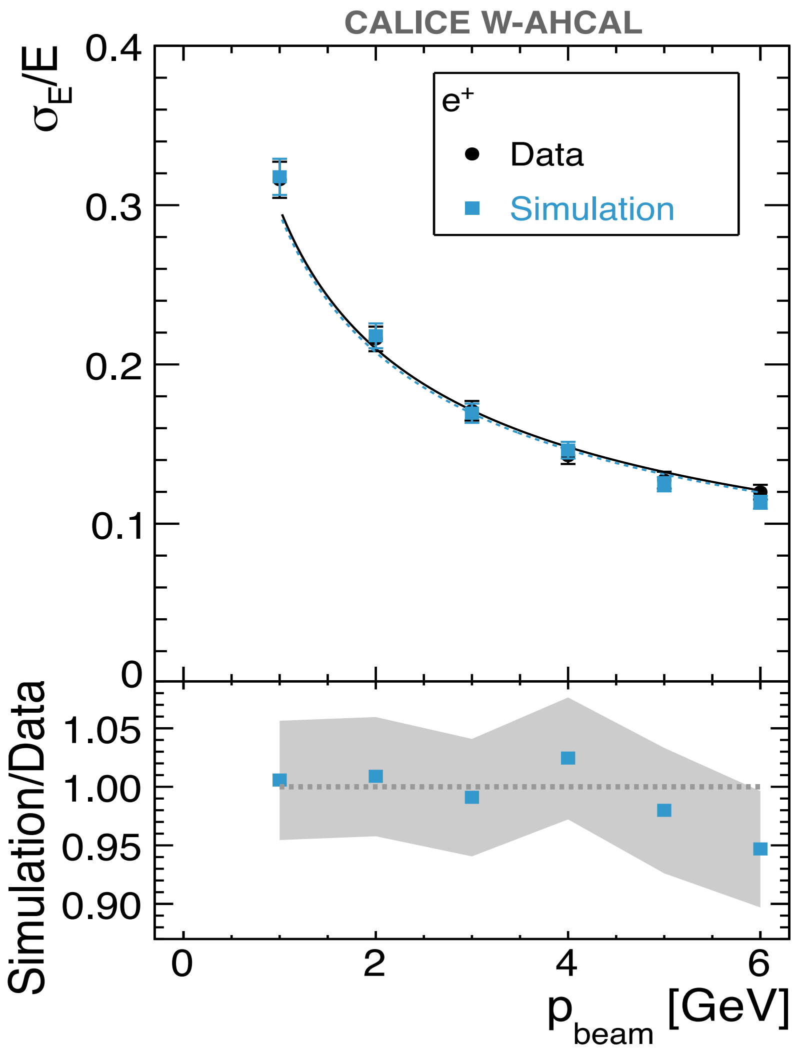


Calorimeter response increases linearly with p_{beam}

Error bands include statistical and systematic uncertainties

Data agree with Monte Carlo simulations within errors to better than 2%

e^+ Resolution at PS (1-6 GeV)



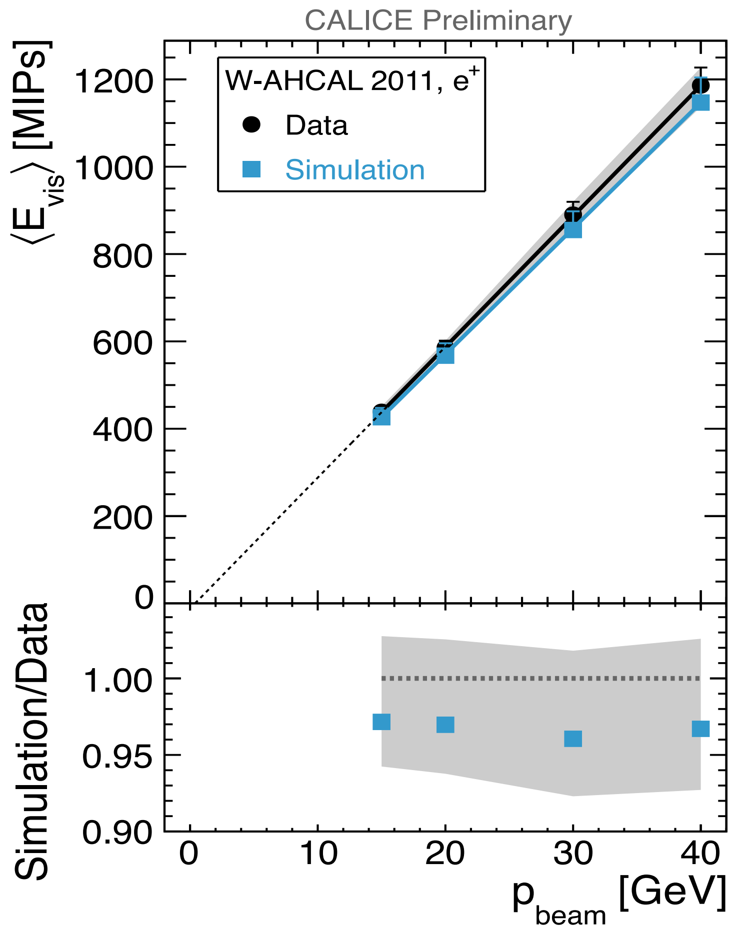
Energy resolution fitted with

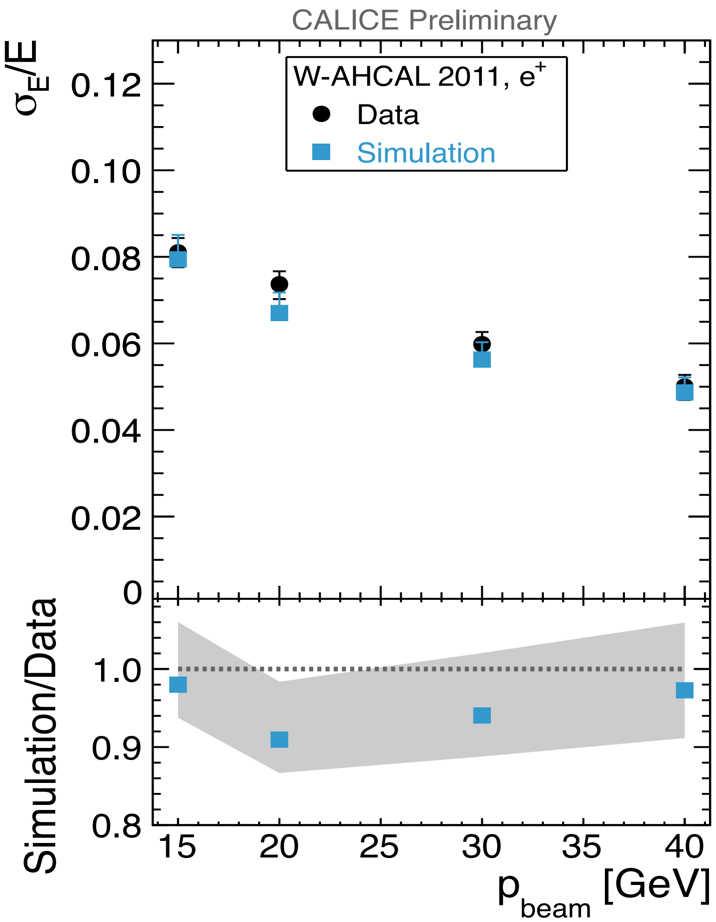
$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E[GeV]}} \oplus b \oplus \frac{c}{E[GeV]}$$

	Data	Simulation
a [%]	29.6 ± 0.5	29.2 ± 0.4
b [%]	0.0 ± 2.1	0.0 ± 1.5
c [GeV]	0.036	0.035

c determined by noise in reference volume

Results for e^+ at SPS (15-40 GeV)





Data and simulation for calorimeter response and resolution agree within large systematic errors

Dense e^+ showers lead to high signals in individual tiles

=> saturation in SiPM needs to be well understood

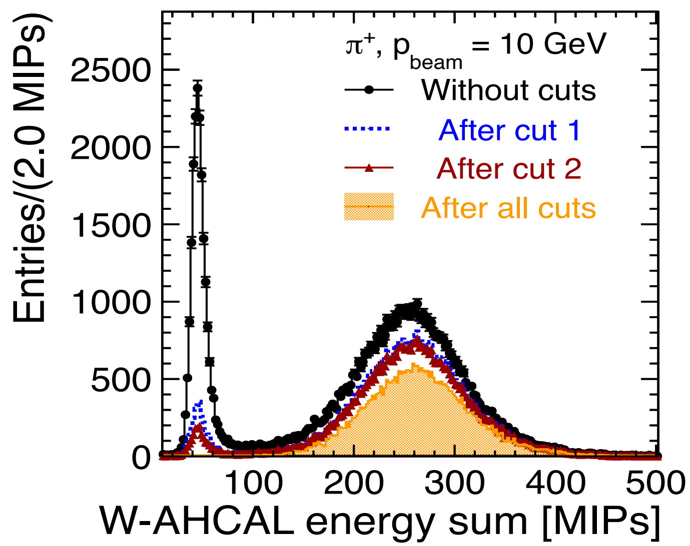
π, K, p Selection

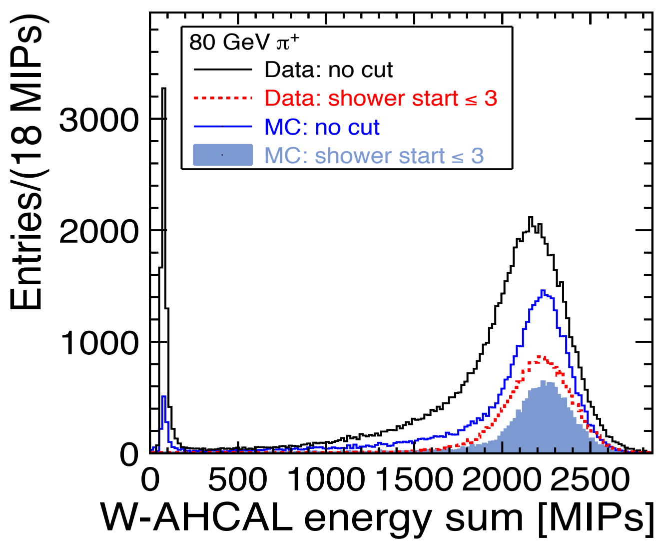
Pre-selection based on 2 threshold Cherenkov counters in beam line filled with CO_2 (PS) or He (SPS)

Reject muon-like or late showering hadrons:

PS data : number/ position of tracks/ clusters in event

SPS data: select events with shower start ≤ 3rd layer



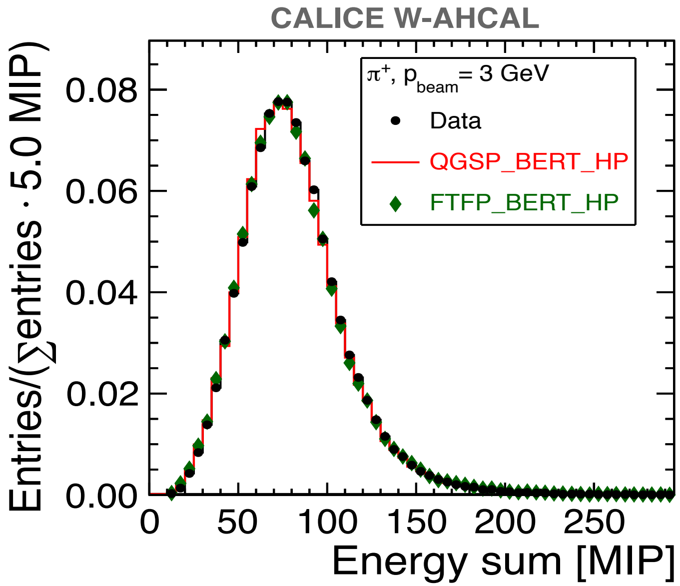


Hadron Signal in W-AHCAL

PS test beam

- Energy sum distributions show high-energy tails for hadron signals (statistical effect, reproduced in MC)
- Effect less pronounced for higher energy (line shape varies with energy)

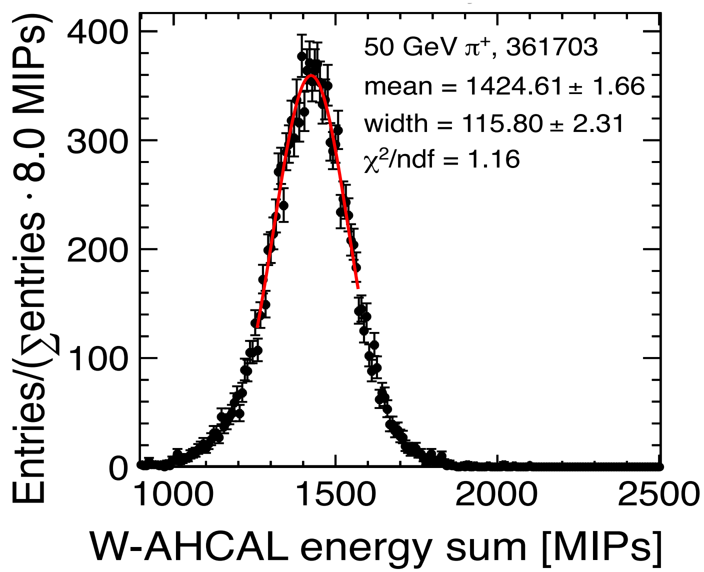
⇒ Use mean and RMS from distribution (E = mean, σ = RMS)



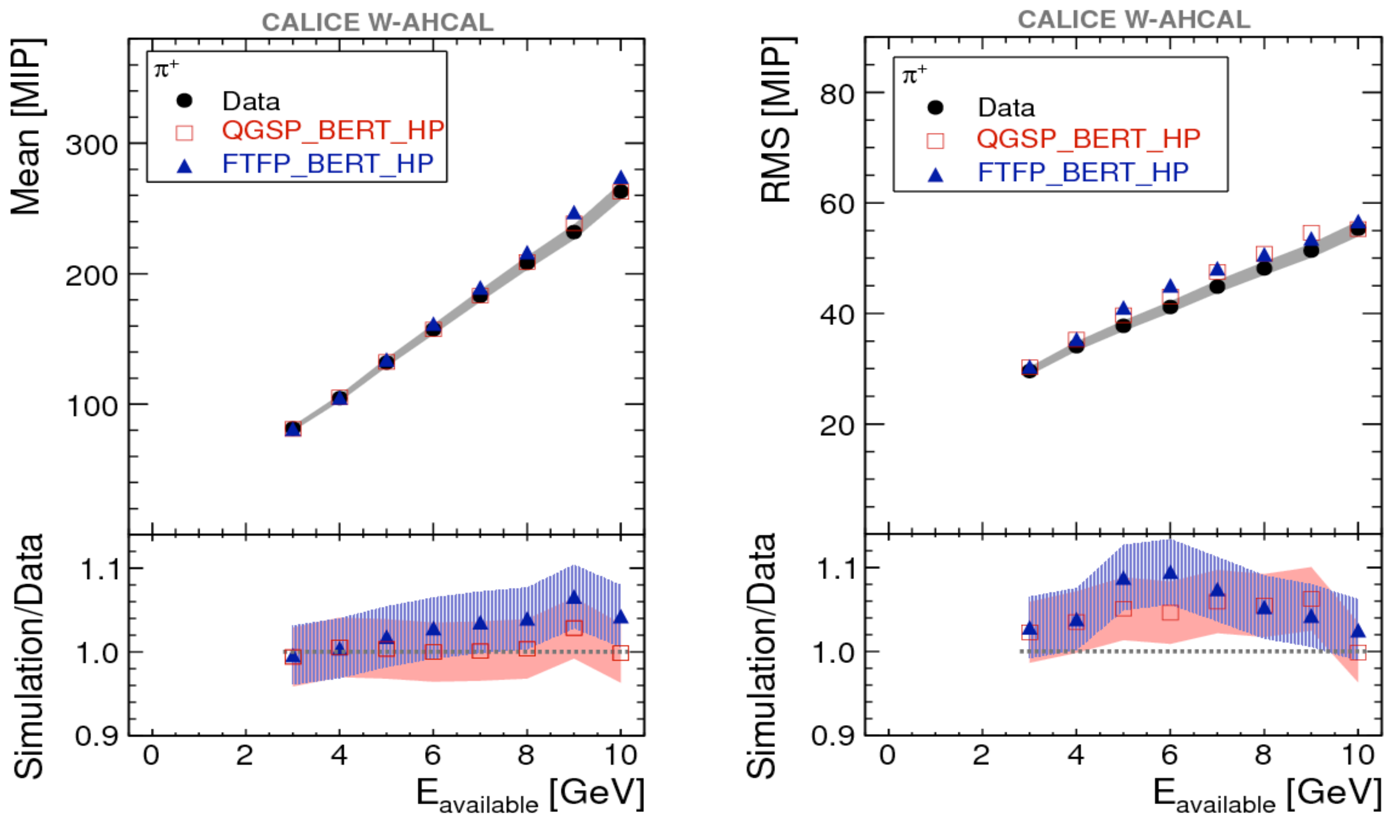
SPS test beam

- At higher energies line shapes are more symmetric and stay similar

⇒ Use Gaussian fit in central region containing 80% of the statistics

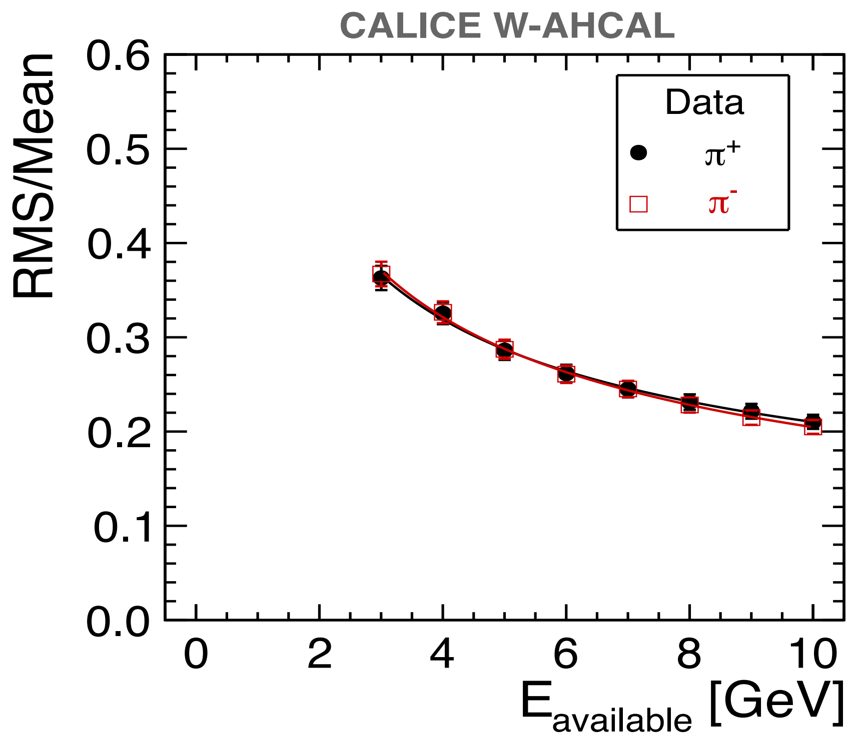


Pion Linearity and RMS at PS (3 – 10GeV)



QGSP_BERT_HP describes mean best, both Monte Carlos give slightly higher RMS values

Pion Resolution at PS (3 – 10GeV)



Energy resolution fitted with

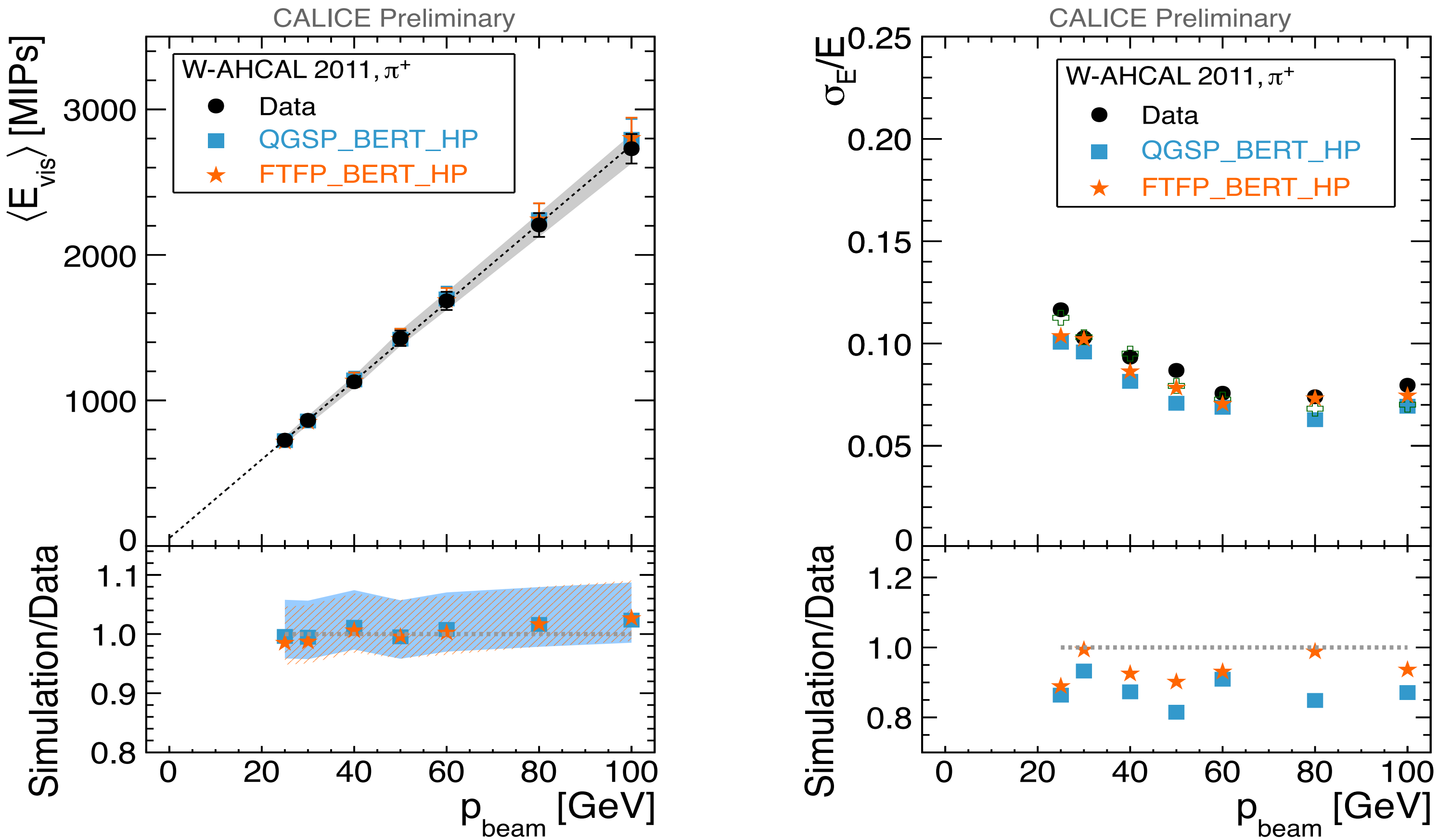
$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E[GeV]}} \oplus b \oplus \frac{c}{E[GeV]}$$

	π^+	π^-
a [%]	63.9 ± 2.4	61.8 ± 2.5
b [%]	3.2 ± 6.9	7.7 ± 3.0
c [GeV]	0.071	0.070

c determined by noise in total detector

b not well constrained by fit

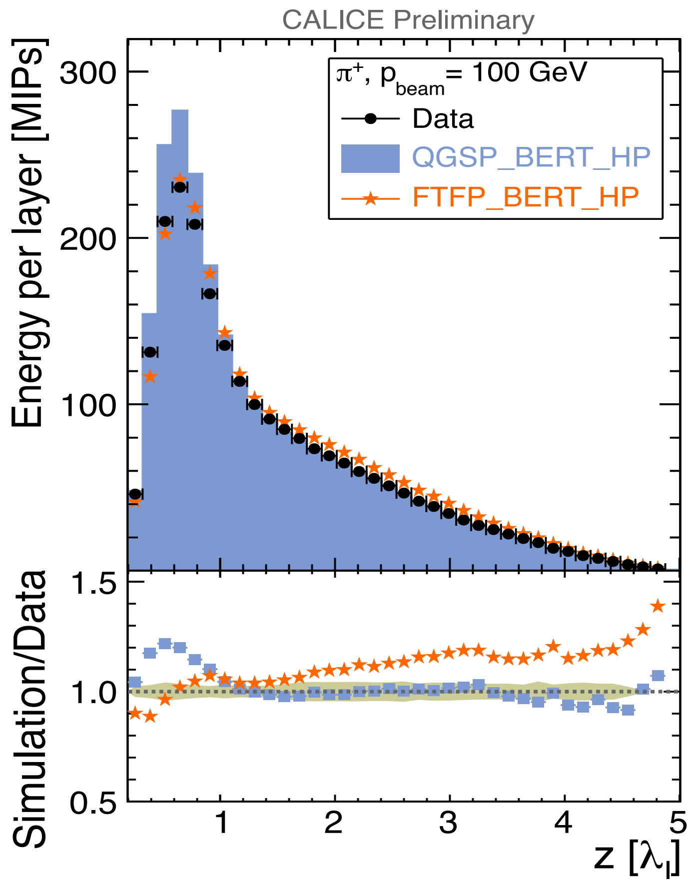
Pion Linearity and Resolution at SPS (25 – 100 GeV)

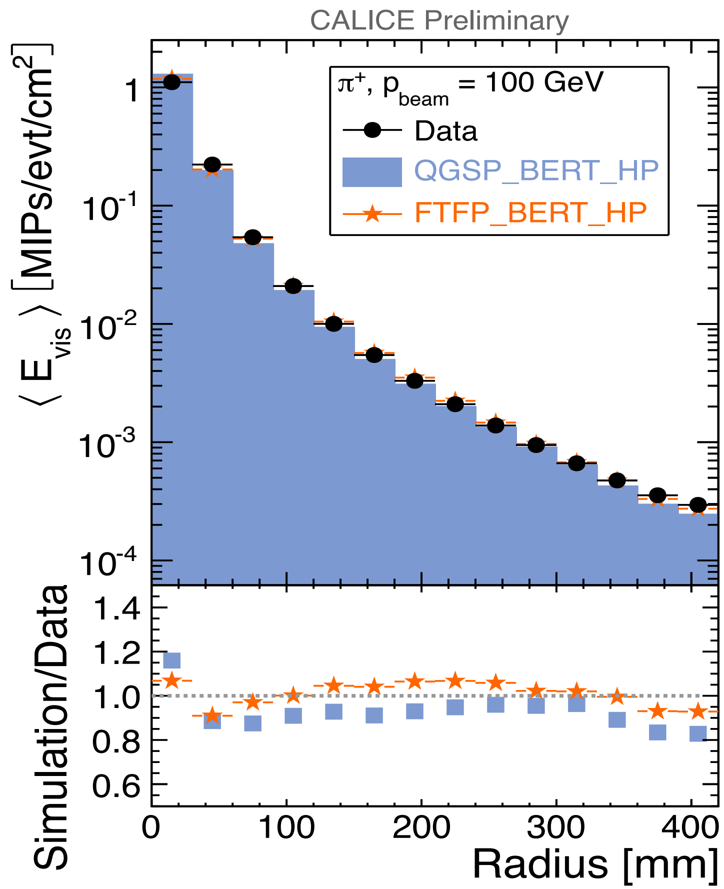


Good agreement between data and QGSP_BERT_HP and FTFP_BERT_HP

Simulations show better energy resolution than data

Pion Shower Shapes

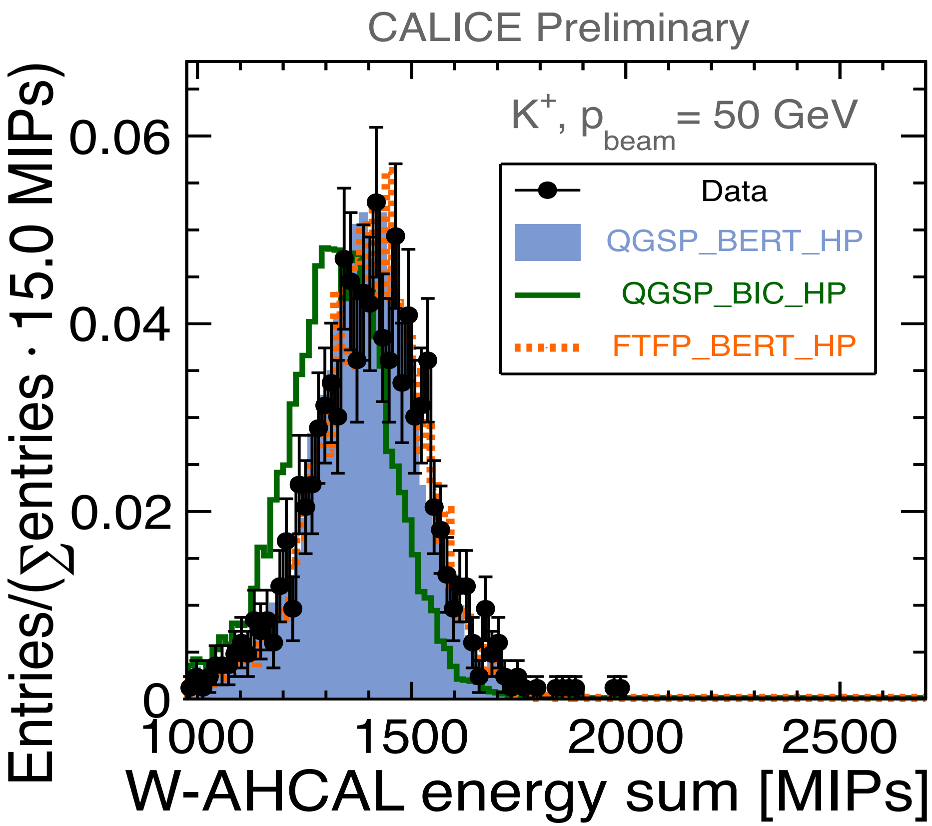




Longitudinal profile (from shower start):
QGSP_BERT_HP overestimates energy deposition in the first layers

Radial profile:
Models overestimate somewhat energy density in shower core

Kaon Signal

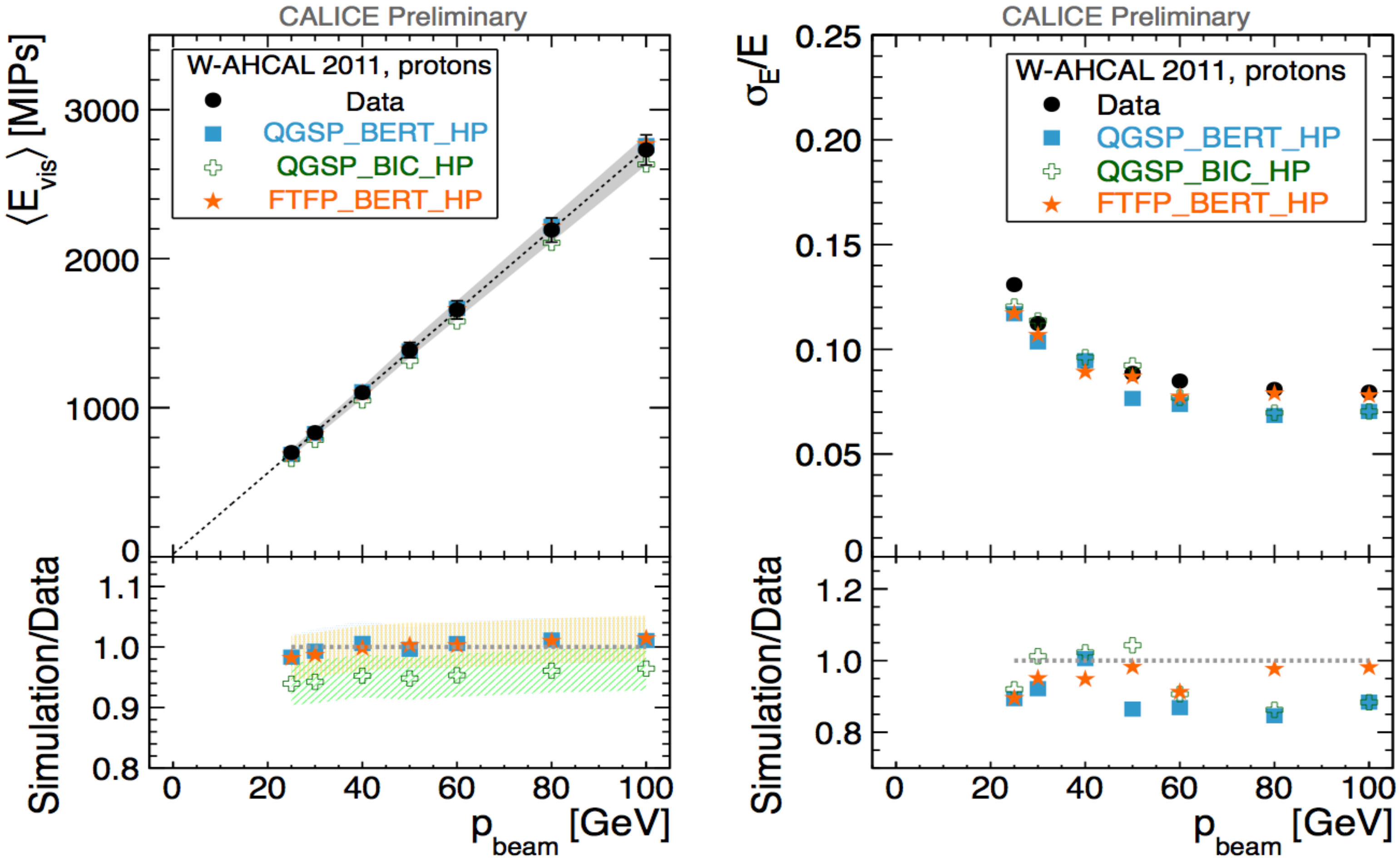


K data measured for 50 and 60 GeV

QGSP_BERT and FTFP_BERT_HP models agree well with experimental data

QGSP_BIC_HP underestimates measured energy

Protons Linearity and Resolution at SPS (25 – 100 GeV)



QGSP_BERT_HP and FTFP_BERT_HP models agree well with calorimeter response

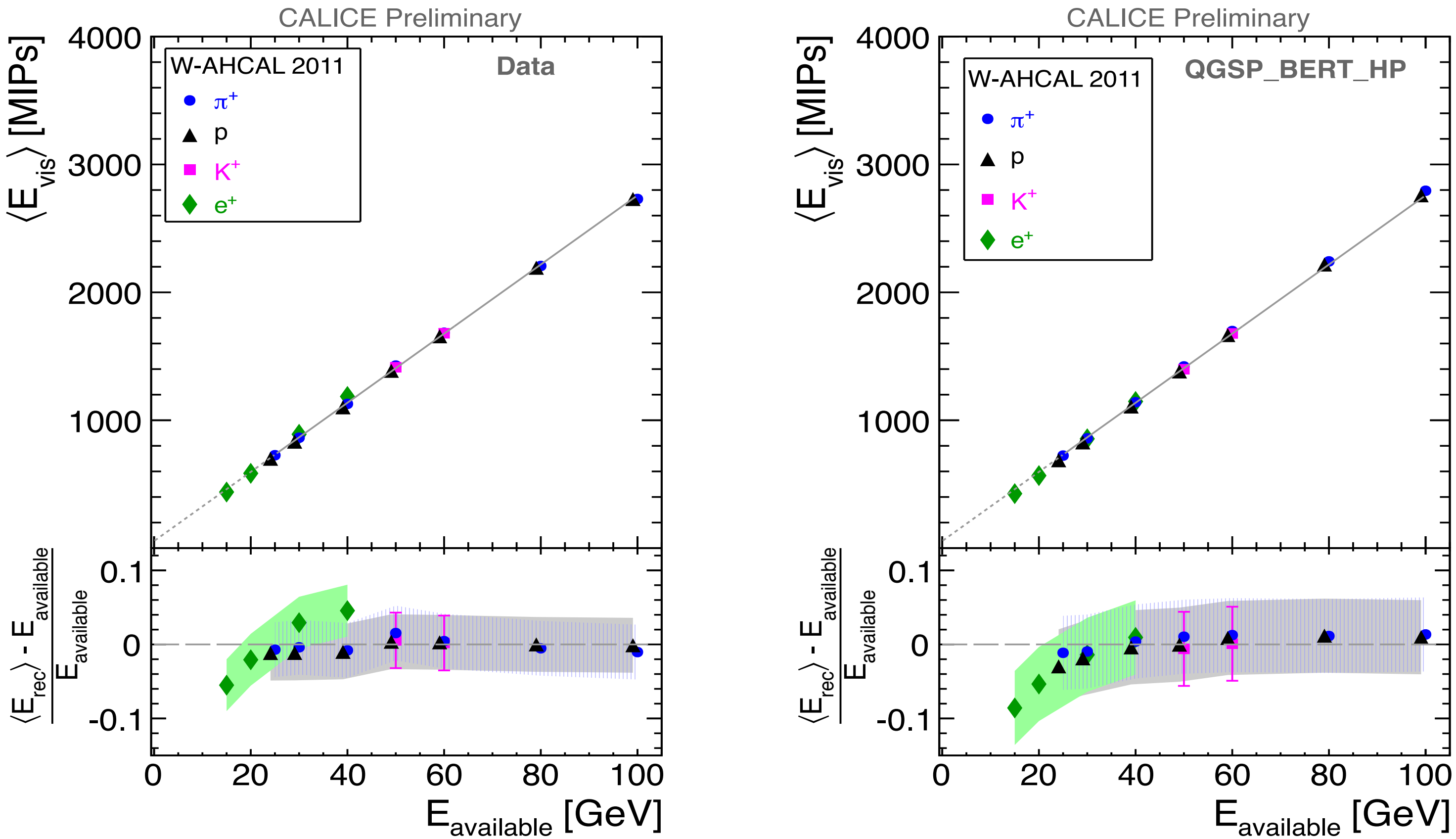
QGSP_BIC_HP underestimates data slightly (within uncertainties)

Simulations show slightly better resolution than data

Calorimeter Response for Different Particle Types

Straight line:

Fit to π^+ data



Data from π^+, K^+ and p agree with fit to better than ≤2% (well within systematic errors)

Data from e^+ show slightly bigger deviations of ≤5% from fit (larger then systematic errors)

Residuals to fit give estimate of level of compensation:

to be compared to $e/\pi_{Fe} \approx 1.19$ [CALICE Fe-AHCAL: JINST 7 (2012) 09017]

Behavior well reproduced by MC

Summary

- A study of e, π, K and p initiated showers in the CALICE highly granular Scintillator-Tungsten HCAL prototype has been presented
- Two measurement campaigns have been analyzed
  - Data from 2010 at CERN PS $1 \leq P_{beam} \leq 10$ GeV
  - Data from 2011 at CERN SPS $15 \leq P_{beam} \leq 100$ GeV
- Results on linearity, resolution and shower shapes have been obtained
- Responses of W-AHCAL to e, π, K and p are similar
- Experimental data agree on a percent level with predictions of selected GEANT 4 models
  QGSP_BERT_HP shows remarkable agreement for π, K and p
  High precision neutron tracking is needed to simulate tungsten absorber
- Analysis for higher energy data with $P_{beam} \leq 300$ GeV is ongoing