

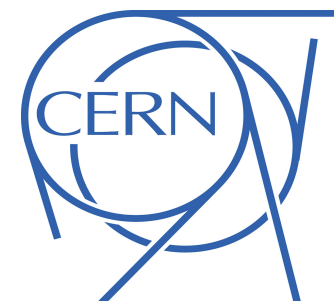


Shower Characteristics of Particles with Momenta up to 100 GeV in the CALICE Scintillator-Tungsten HCAL

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on behalf of the CALICE collaboration
and the CLICdp collaboration

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Hadron Calorimeter at multi-TeV CLIC

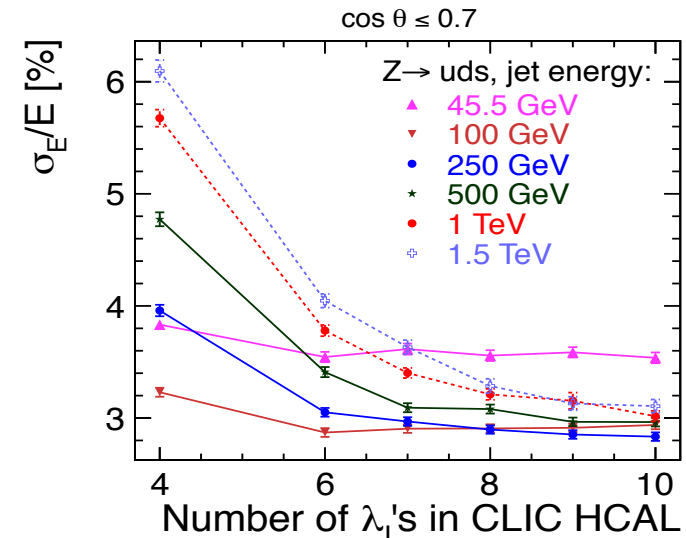
Requirements:

- 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

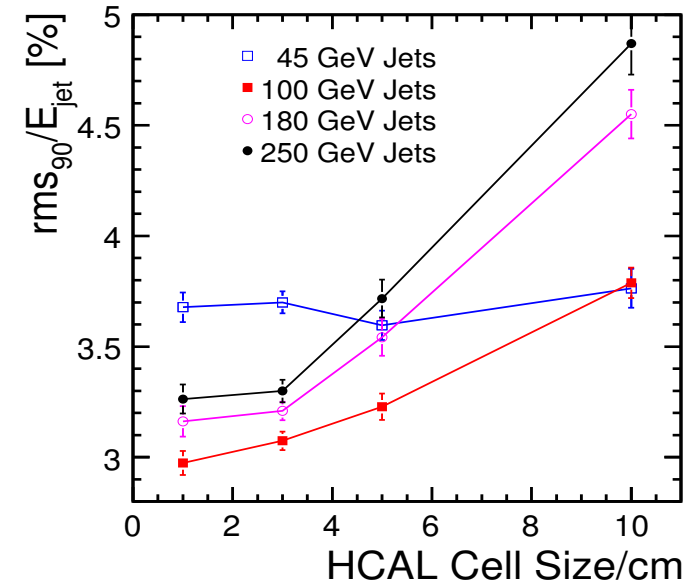
Possible solution:

- 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 $\sigma(p_T)/p_T^2 \sim 2 \cdot 10^{-5} \text{ GeV}^{-1}$
 - Energy of photons (30%) in ECAL $\sigma/E \leq 20\%/VE$
 - energy of neutral hadrons(10%) in HCAL $\sigma(E)/E > 50\% / VE(\text{GeV})$

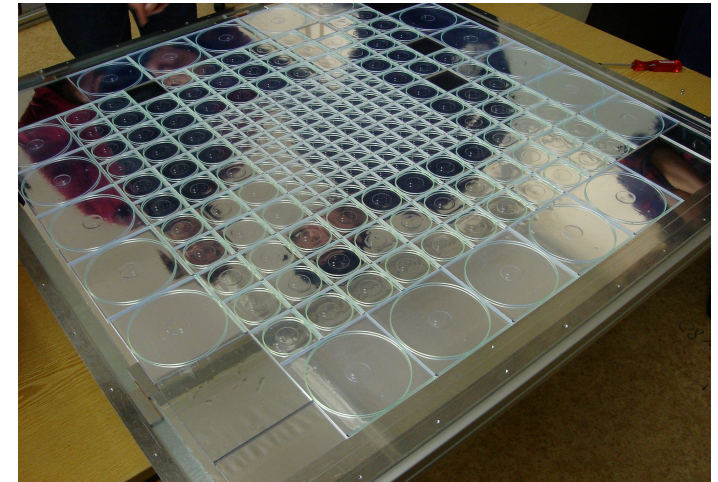
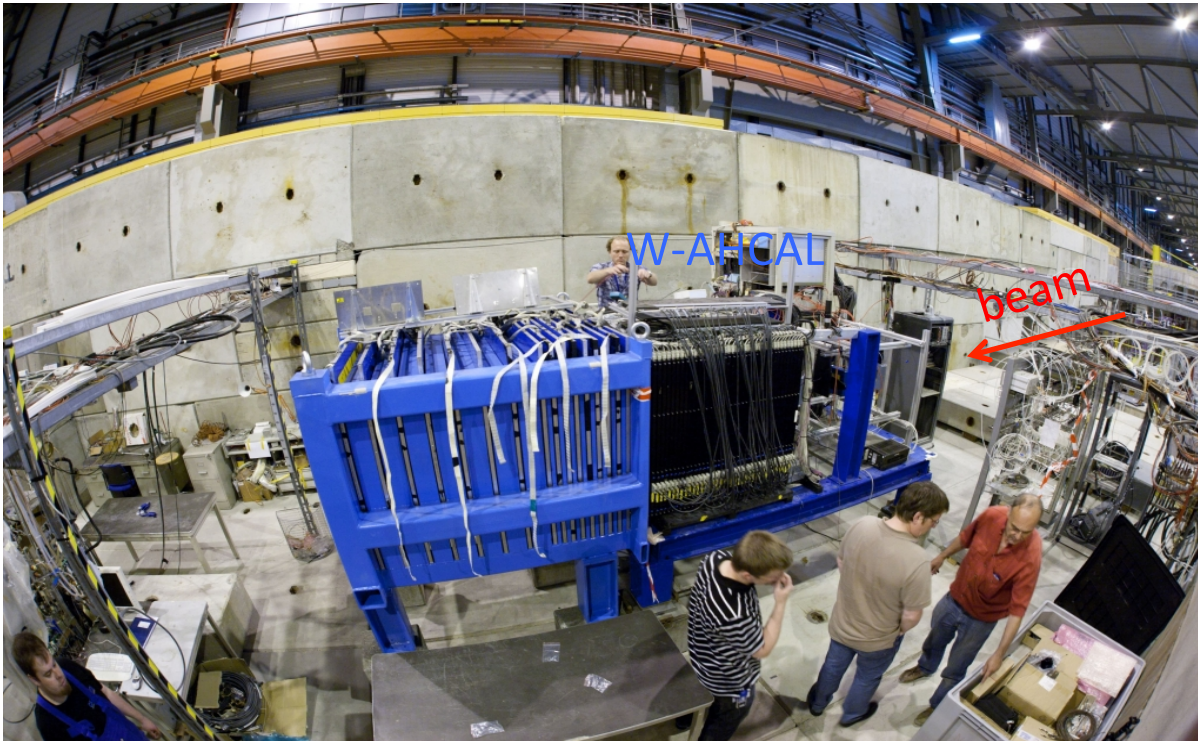
=> Need highly granular and compact calorimeters



(From CLIC CDR, CERN-2012-003)

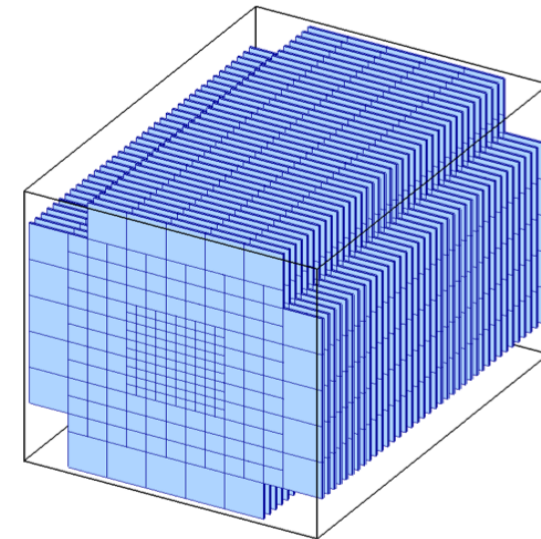


CALICE W-AHCAL Prototype



Scintillator layer

- Sandwich calorimeter:
1cm thick W absorber plates interleaved with 0.5cm thick scintillator tiles
- Granularity: 3 x 3 cm² tiles in central region, surrounded by 6 x 6 cm² and 12 x 12 cm² tiles
- Analogue readout: wavelength shifting fibers connected to Silicon Photomultipliers (SiPM)



Full prototype

Two Measurement Campaigns at CERN PS and SPS

2010 at CERN PS beam line T9

- $1 \text{ GeV} \leq p_{\text{beam}} \leq 10 \text{ GeV}$
- Beam composition: e^{\pm} , μ^{\pm} , π^{\pm} , p
- Beam line equipped with 2 threshold Cherenkov counters filled with CO_2 , $0 \leq p \leq 3.5 \text{ bar}$
- W-AHCAL consisting of 30 layers corresponding to $3.9 \lambda_1$ 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

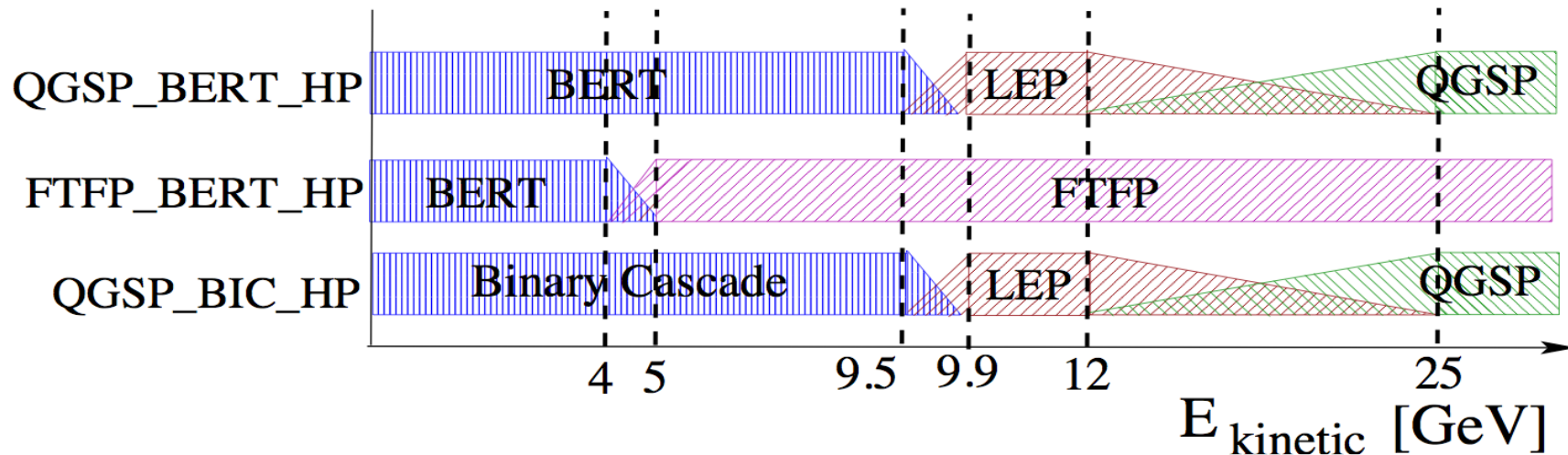
2011 at CERN SPS beam line H8

- $10 \text{ GeV} \leq p_{\text{beam}} \leq 300 \text{ GeV}$
- Beam composition: e^{\pm} , μ^{\pm} , π^{\pm} , K^{\pm} , p
- Target choice: e^{\pm} - beam versus hadron beam
- Beam line equipped with 2 threshold Cherenkov counters filled with He, $0 \leq p \leq 3 \text{ bar}$
- Dedicated μ^{\pm} beams (Fe dump upstream of experiment) for calibration
- W-AHCAL consisting of 38 layers corresponding to $4.9 \lambda_1$ 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

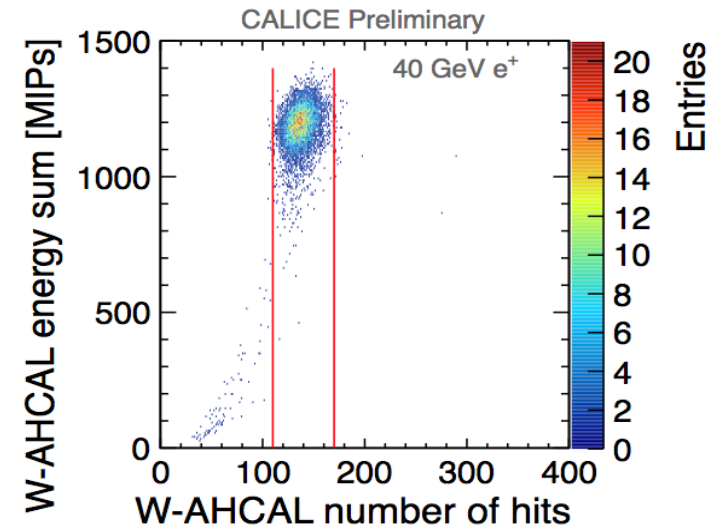
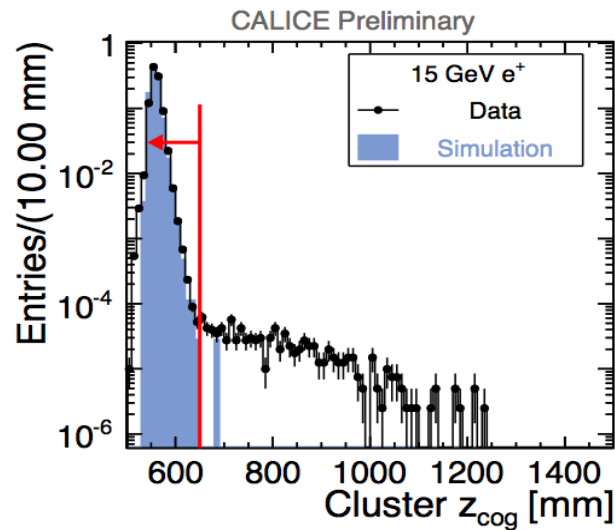
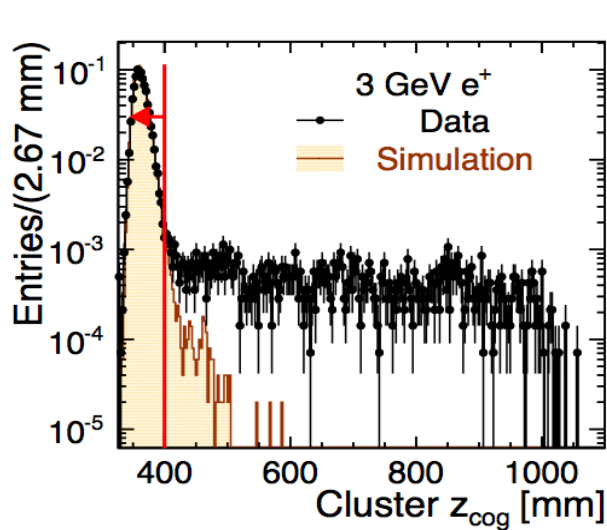
Electron Selection

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 = $f(p_{\text{beam}})$

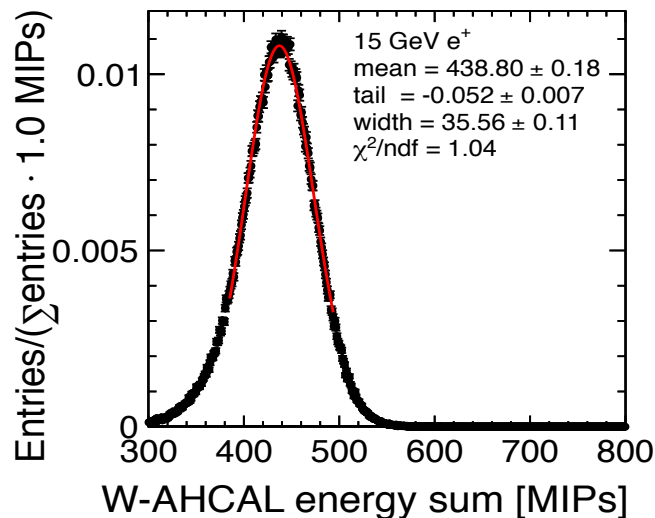
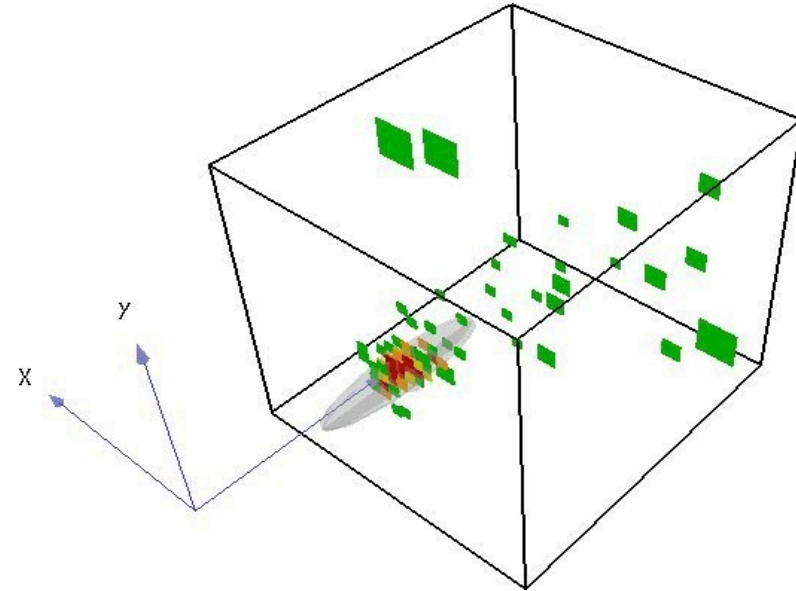


Electron Signal in W-HACAL

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

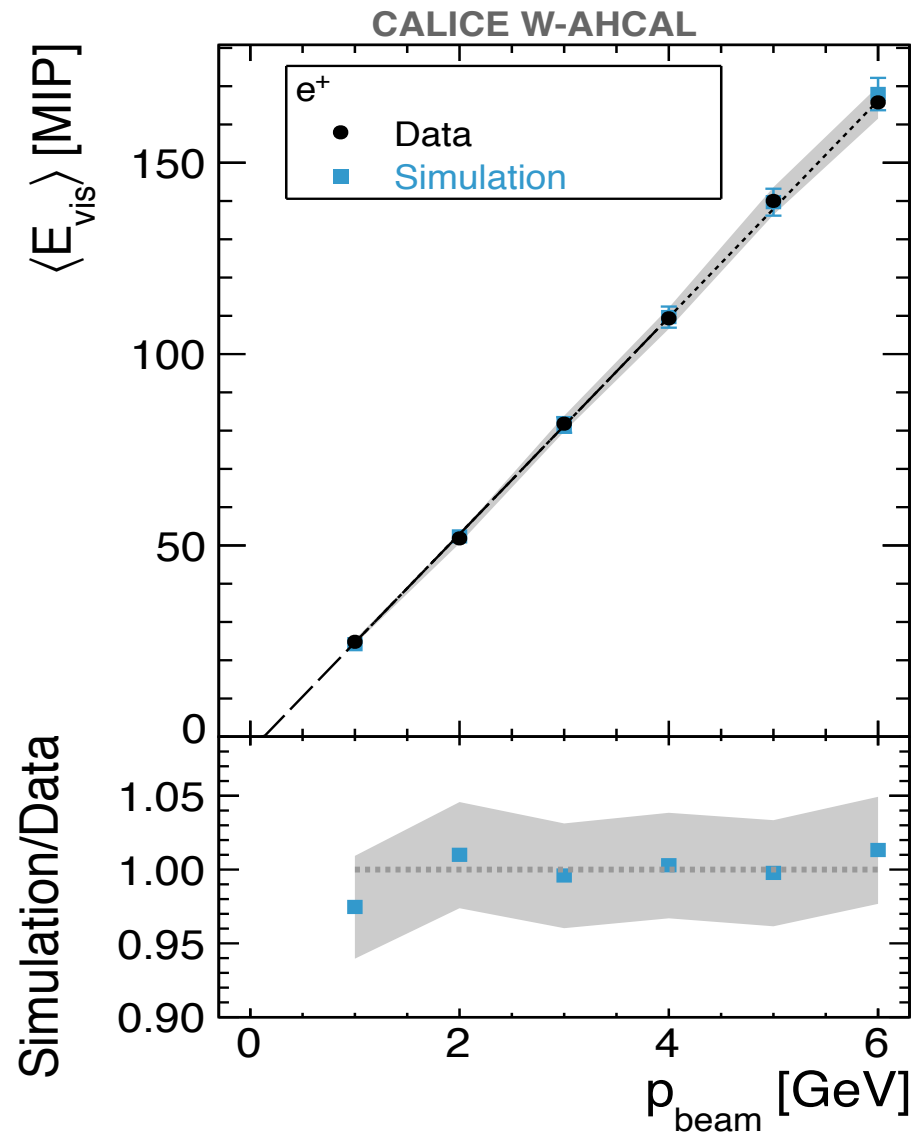
For energy evaluation consider only signals in
first 20 layers of central $3 \times 3 \text{ cm}^2$ tiles
 \Rightarrow reduction in noise

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



Line shape slightly asymmetric:
Fit signal with Novosibirsk function
within $\pm 1.5 \sigma$
(Gaussian with a tail)

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

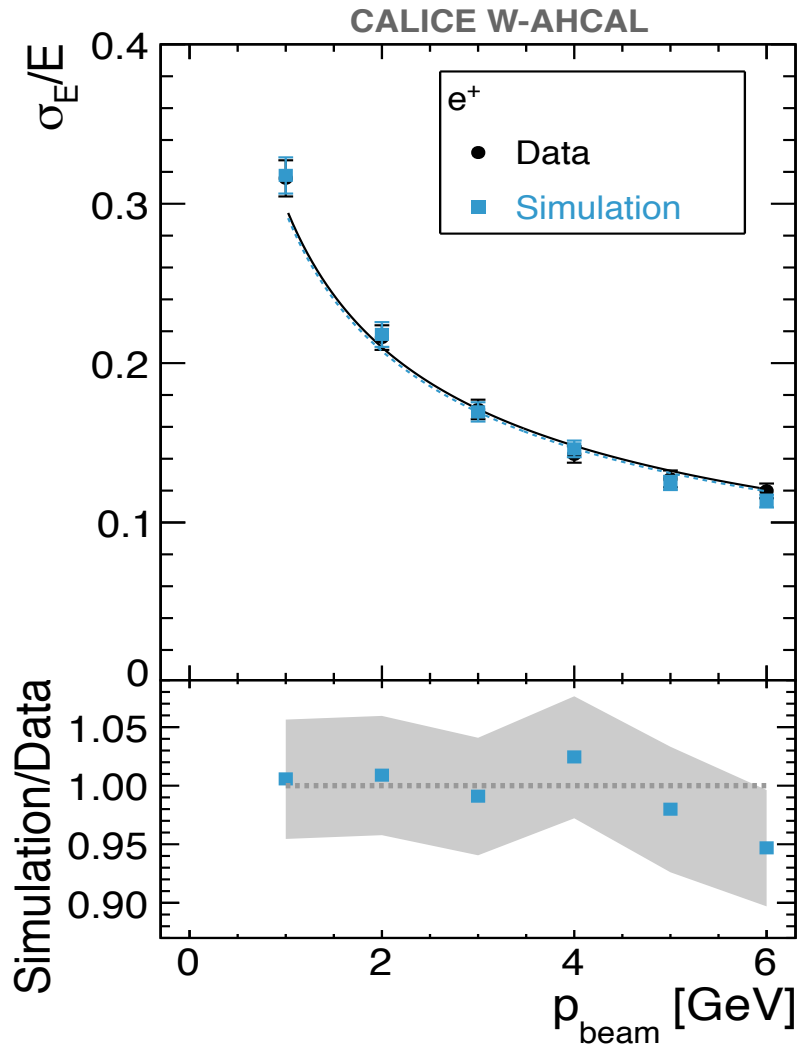


Calorimeter response increases linearly with p_{beam}

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)



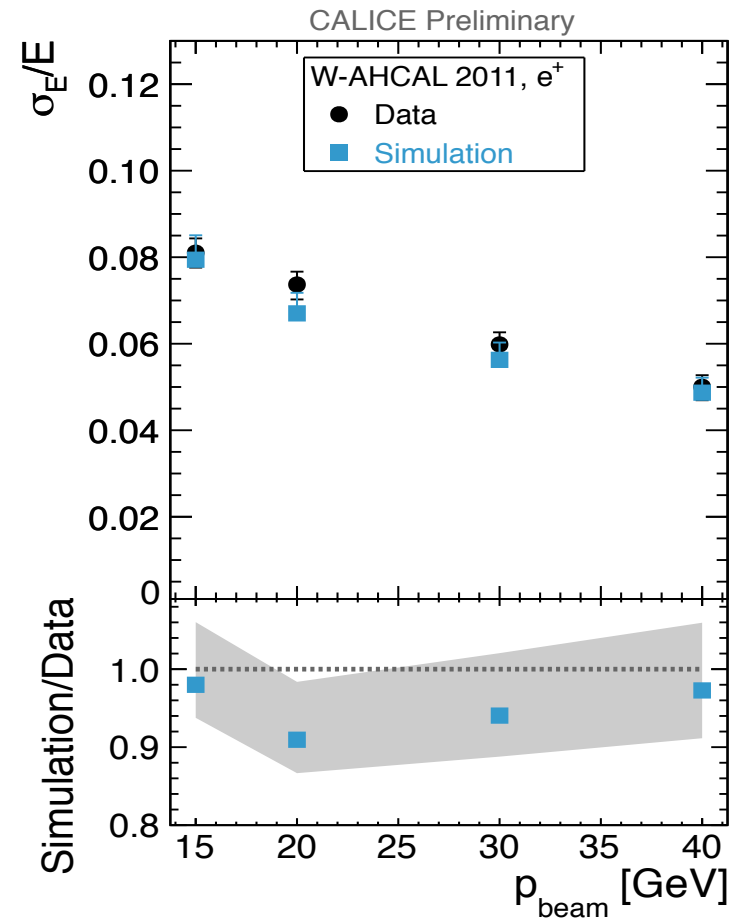
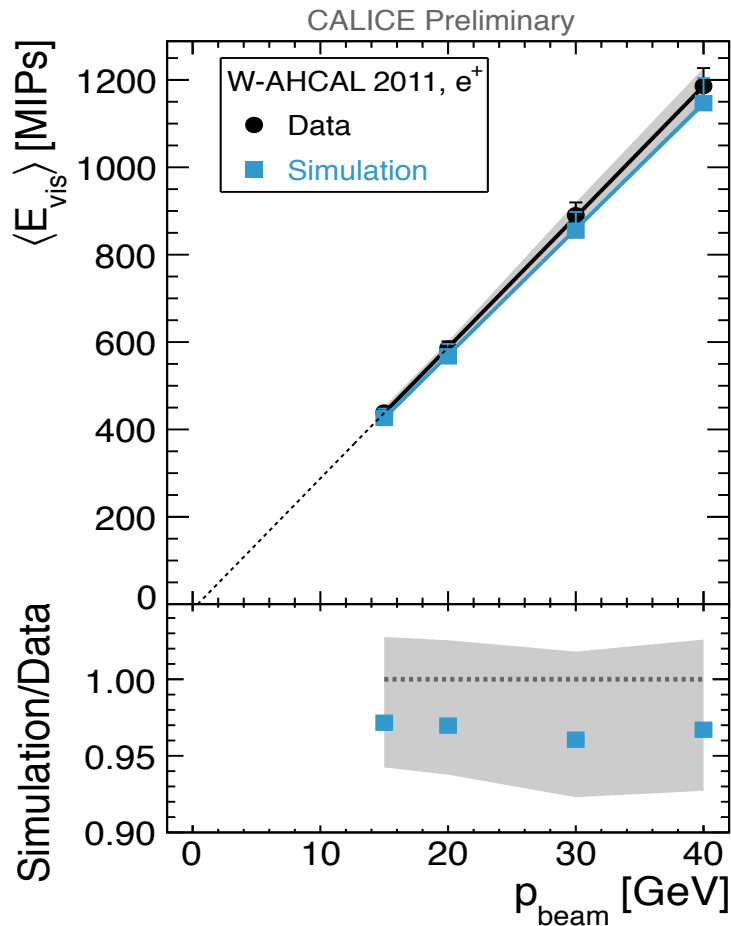
Energy resolution fitted with

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

	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

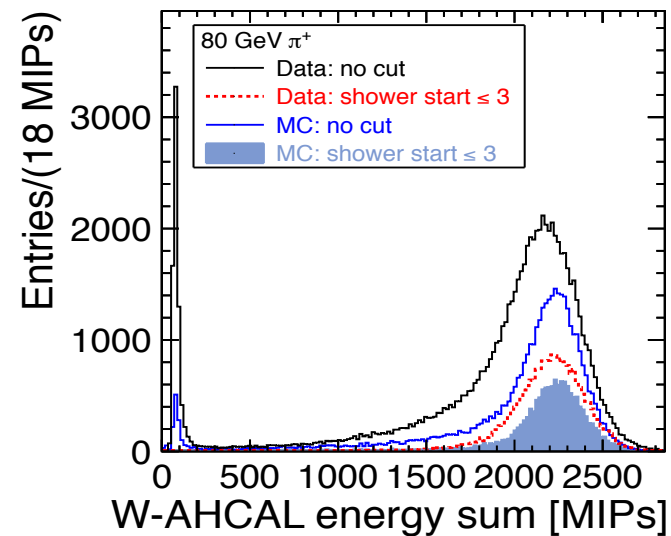
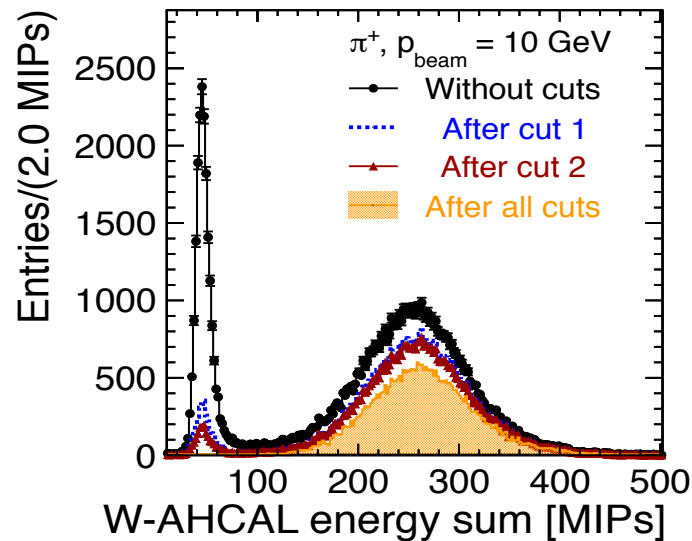
π , K , p Selection

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 \leq 3rd layer



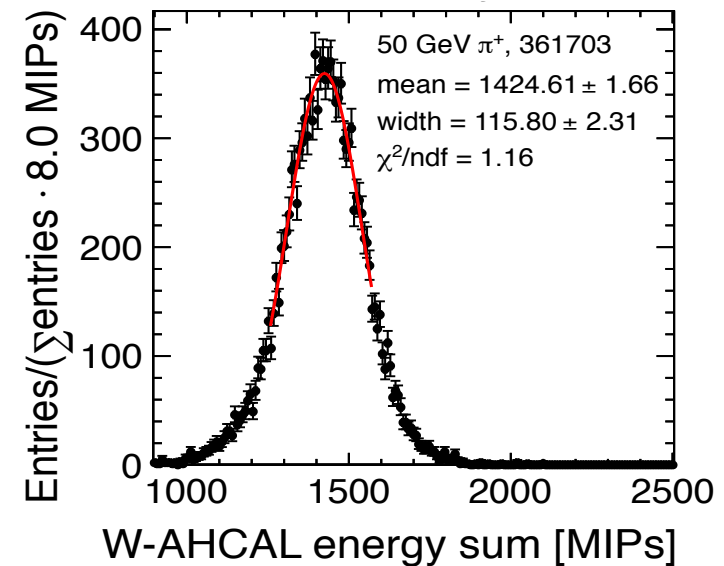
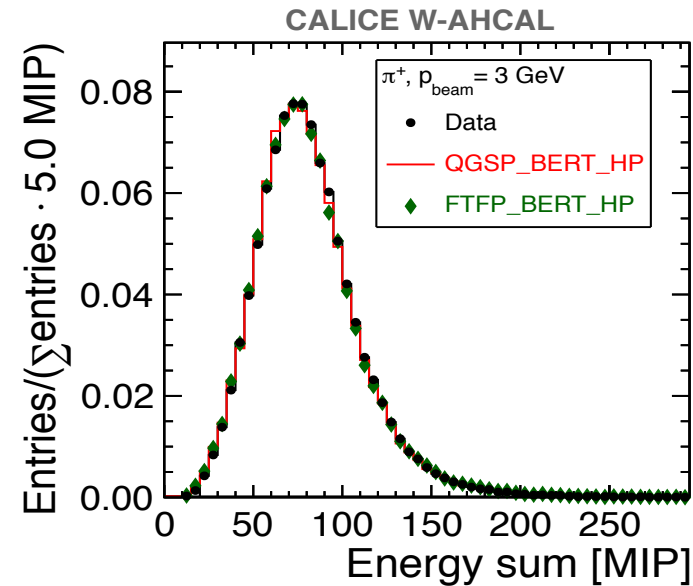
Hadron Signal in W-AHCAL

PS test beam

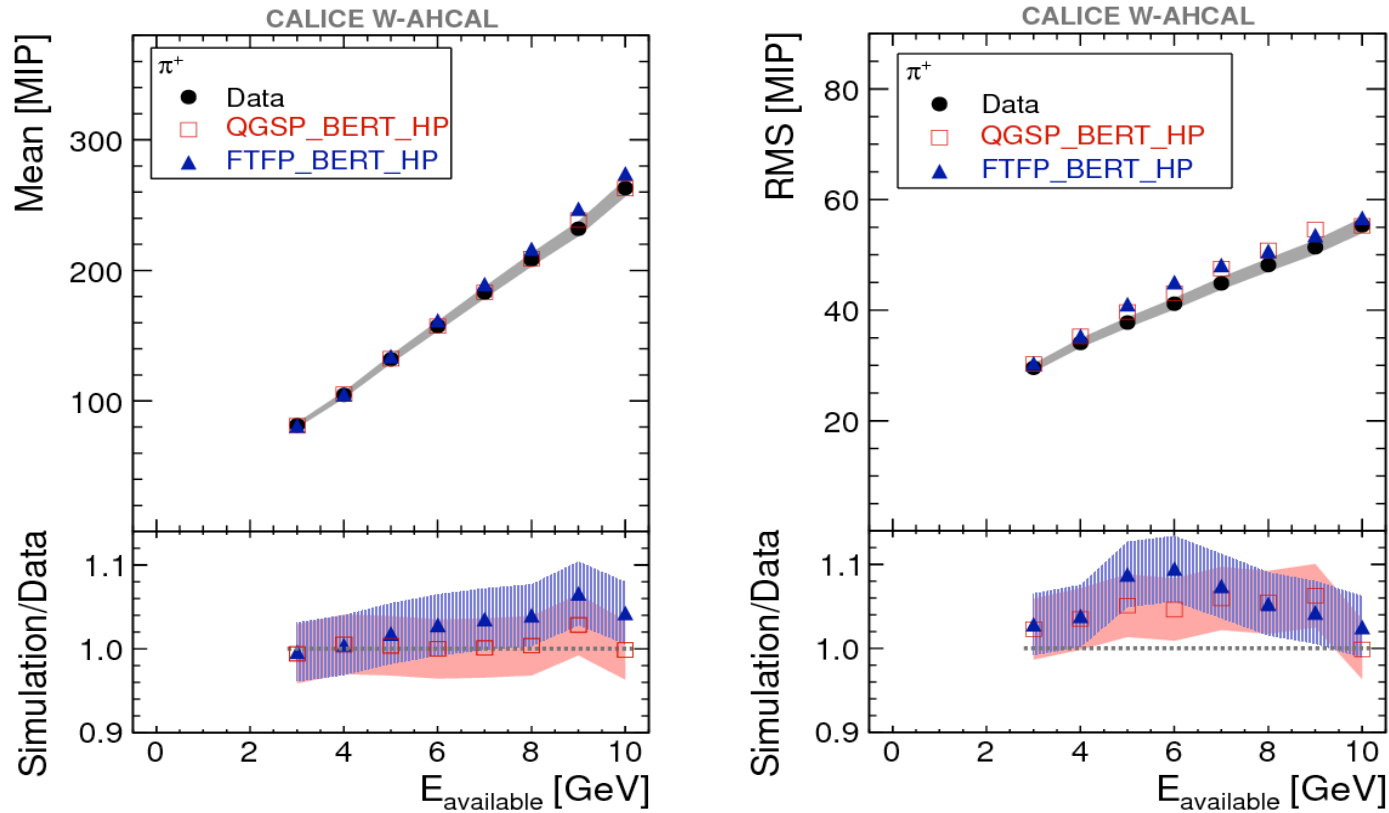
- Energy sum distributions show high-energy tails for hadron signals (statistical effect, reproduced in MC)
 - Effect less pronounced for higher energy (line shape varies with energy)
- ⇒ Use mean and RMS from distribution ($E = \text{mean}$, $\sigma = \text{RMS}$)

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

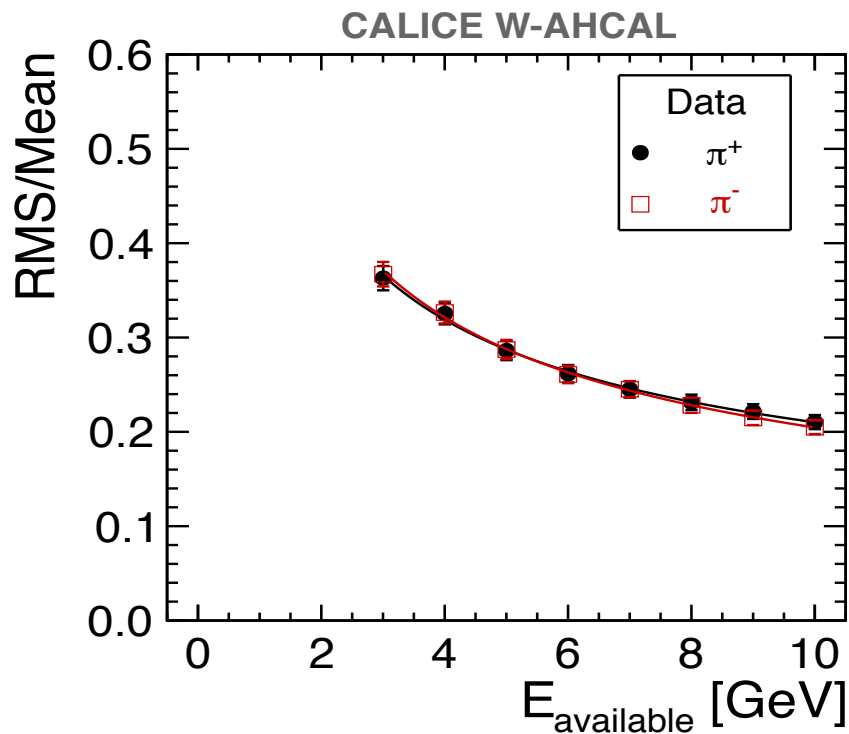


Pion Linearity and RMS at PS (3 – 10GeV)



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

Pion Resolution at PS (3 – 10GeV)



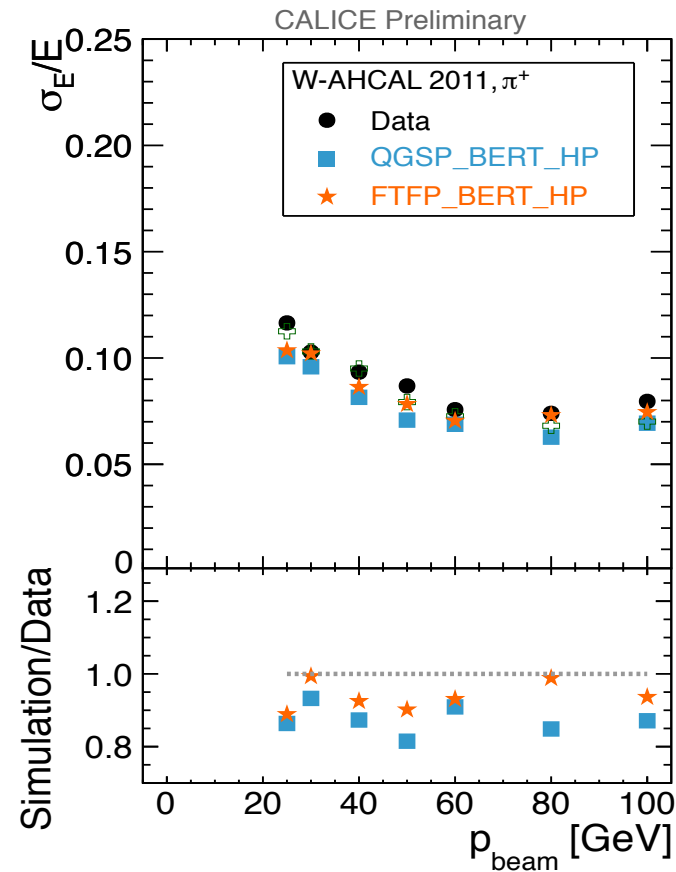
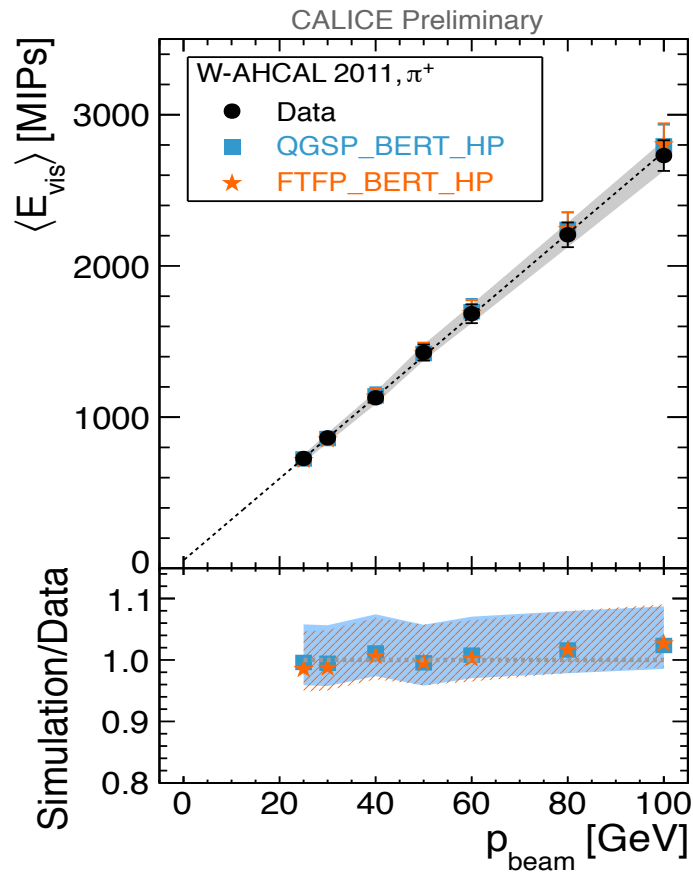
Energy resolution fitted with

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

	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

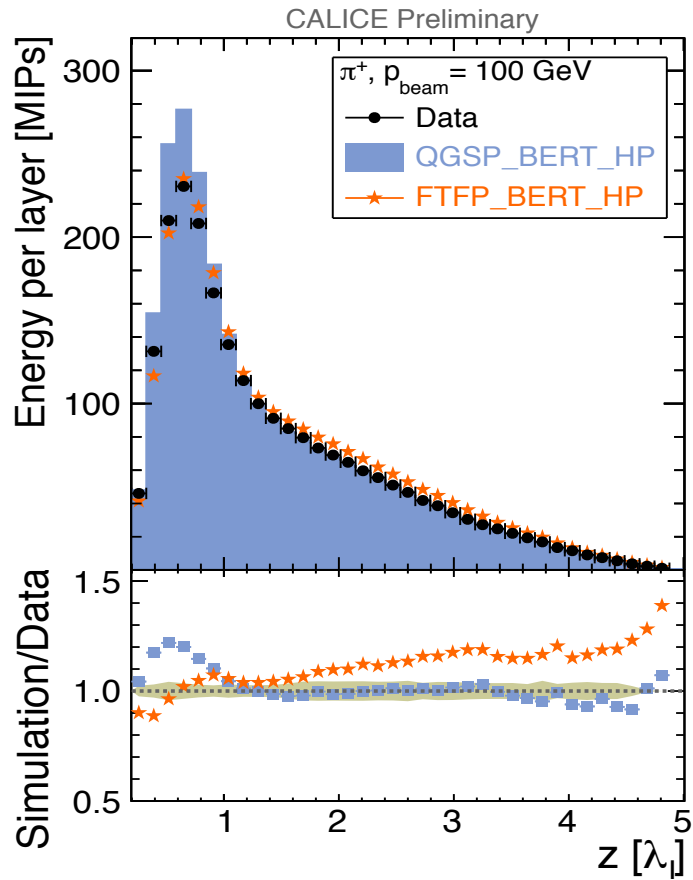
c determined by noise in total detector
 b not well constrained by fit

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

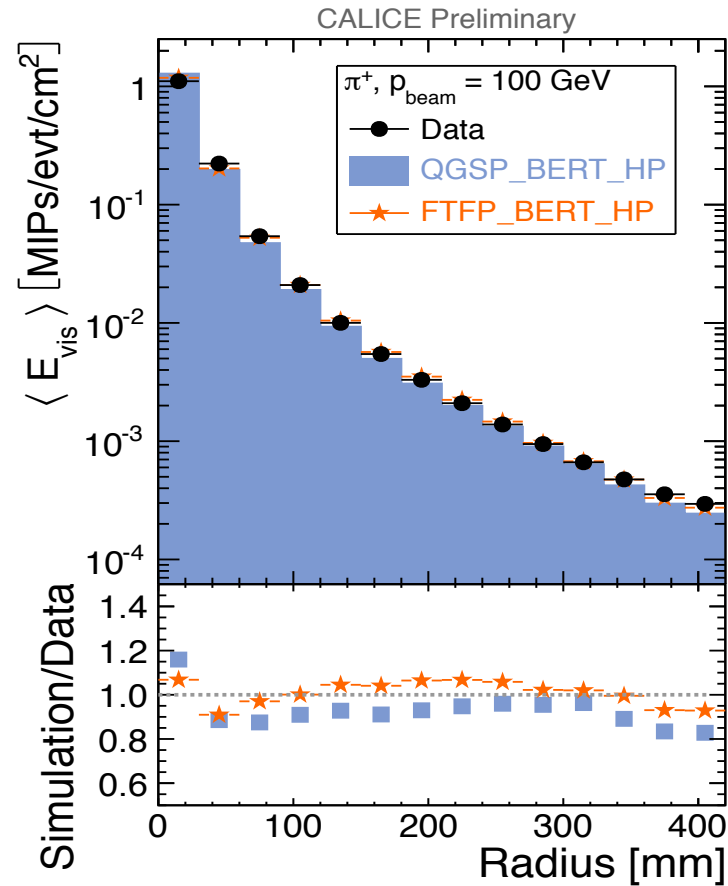


Good agreement between data and QGSP_BERT_HP and FTFP_BERT_HP
Simulations show better energy resolution than data

Pion Shower Shapes

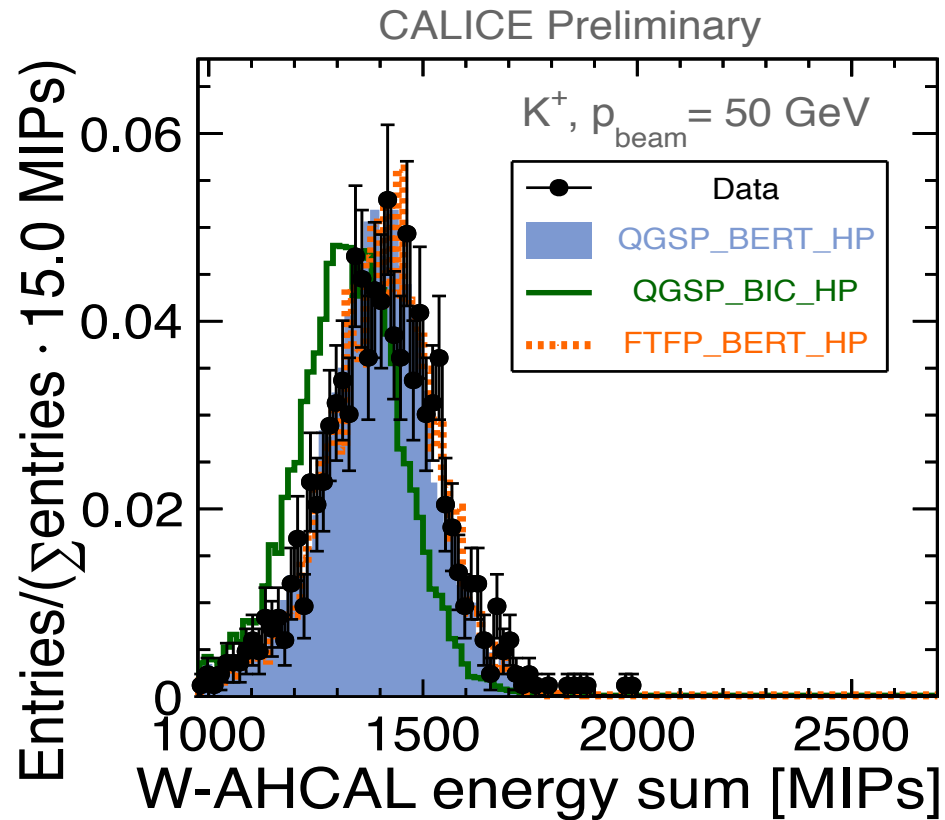


Longitudinal profile (from shower start):
QGSP_BERT_HP overestimates energy
 deposition in the first layers



Radial profile:
 Models overestimate somewhat energy
 density in shower core

Kaon Signal

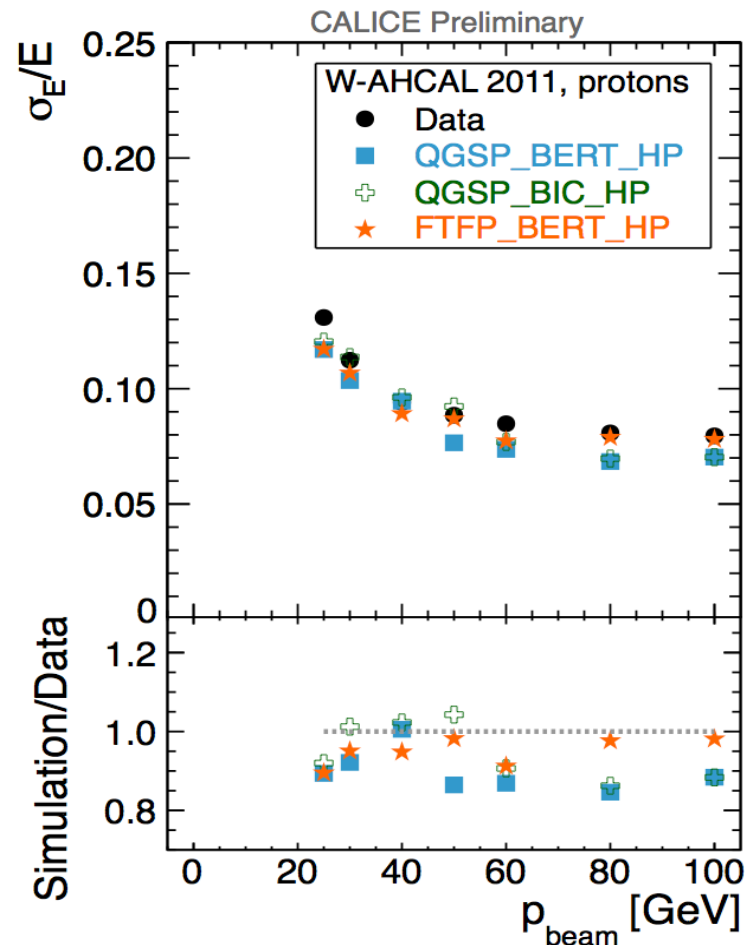
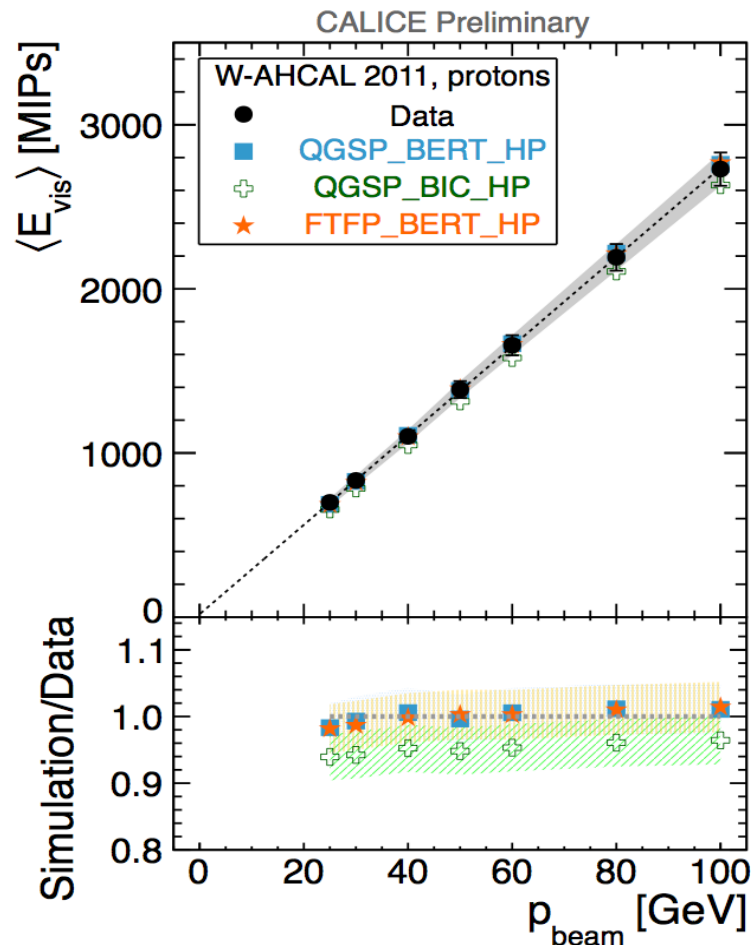


K data measured for 50 and 60 GeV

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)



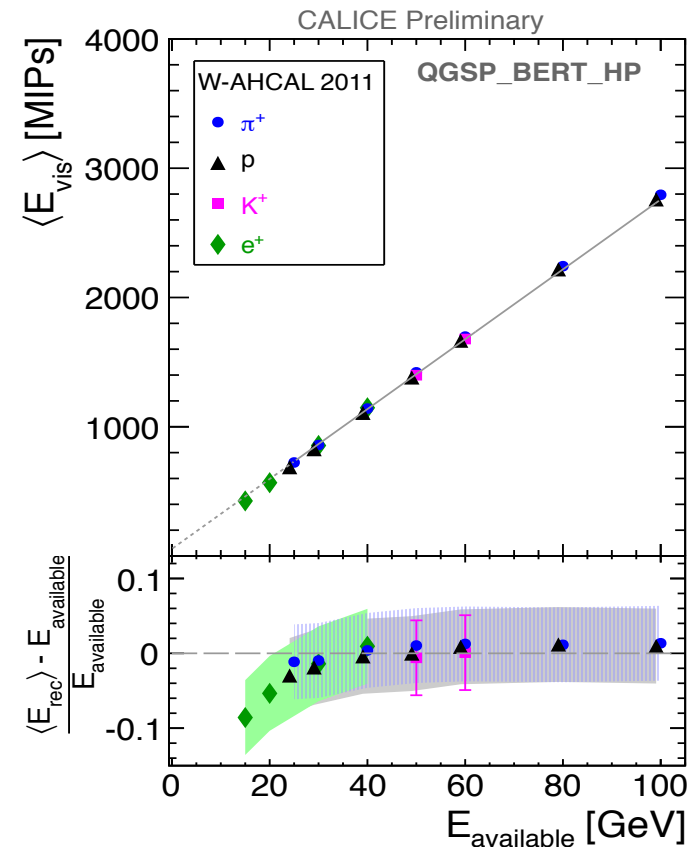
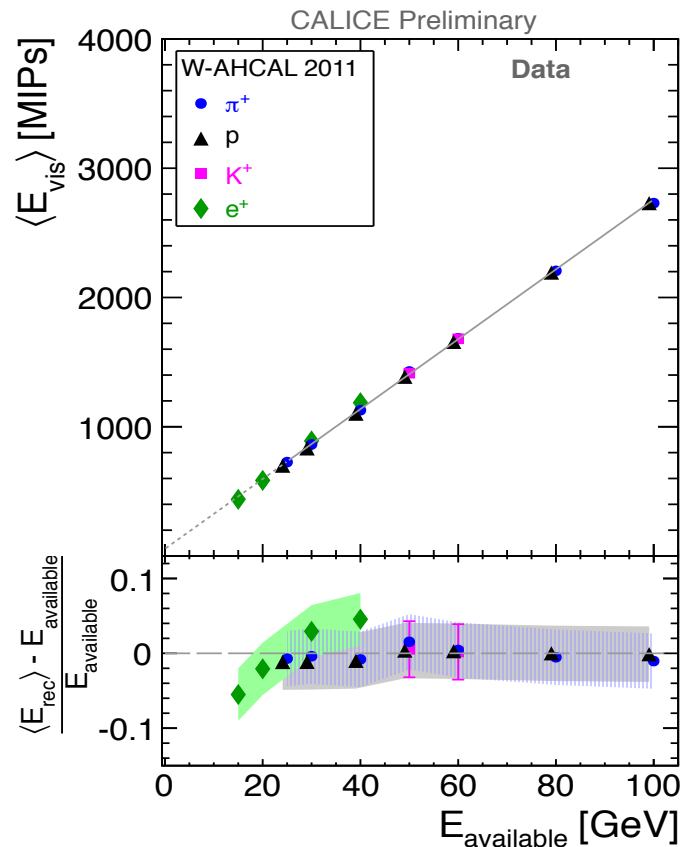
QGSP_BERT_HP and FTFP_BERT_HP models agree well with calorimeter response

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 $\leq 2\%$ (well within systematic errors)

Data from e^+ show slightly bigger deviations of $\leq 5\%$ from fit (larger than systematic errors)

Residuals to fit give estimate of level of compensation:

to be compared to $e/\pi_{\text{Fe}} \approx 1.19$ [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 $1 \leq P_{\text{beam}} \leq 10$ GeV
 - Data from 2011 at CERN SPS $15 \leq P_{\text{beam}} \leq 100$ 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 $P_{\text{beam}} \leq 300$ GeV is ongoing