Exploring the structure of hadronic showers and the hadronic energy reconstruction with highly granular calorimeters

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on behalf of the CALICE collaboration

ICHEP2020, Jul. 31st, 2020

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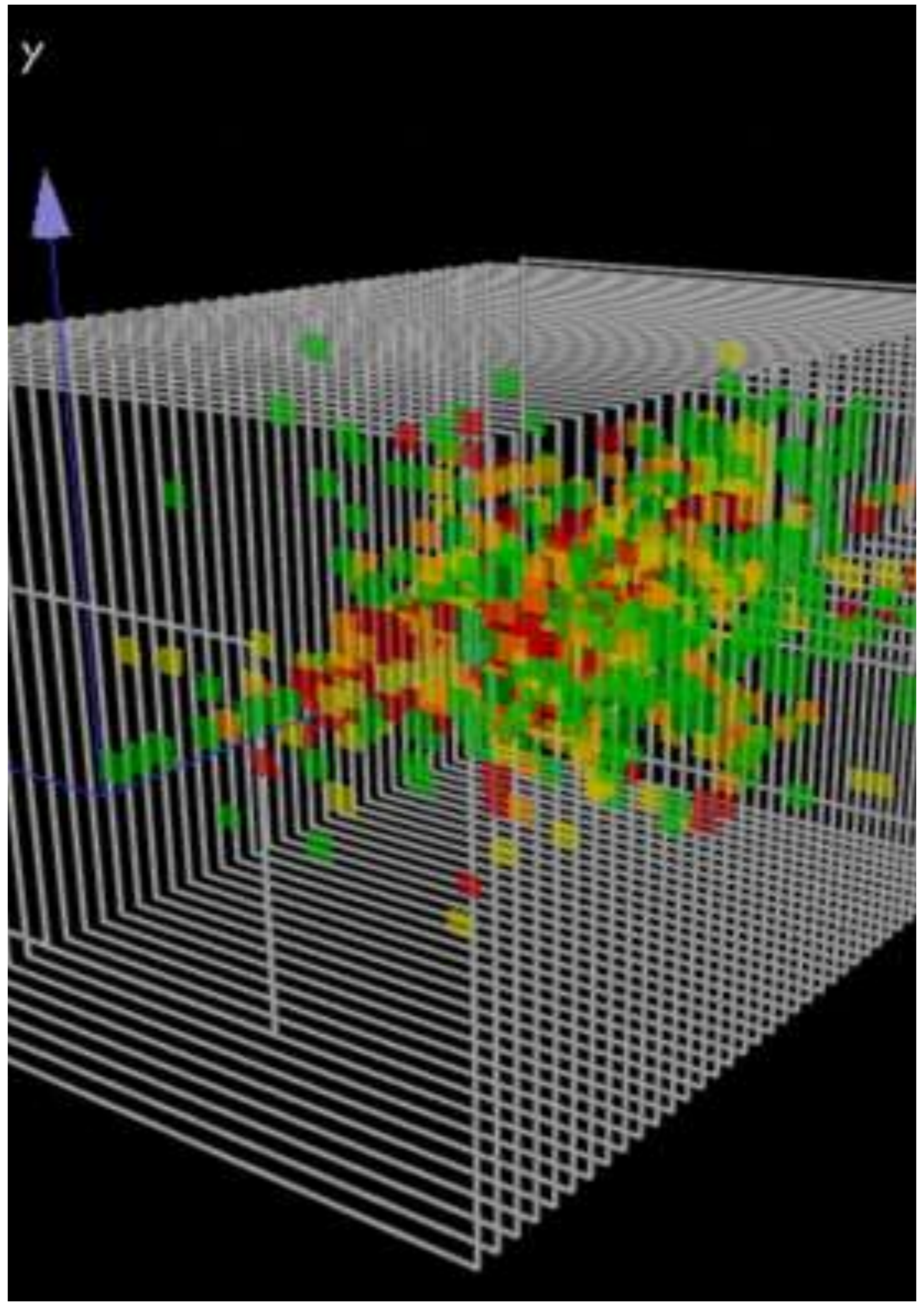
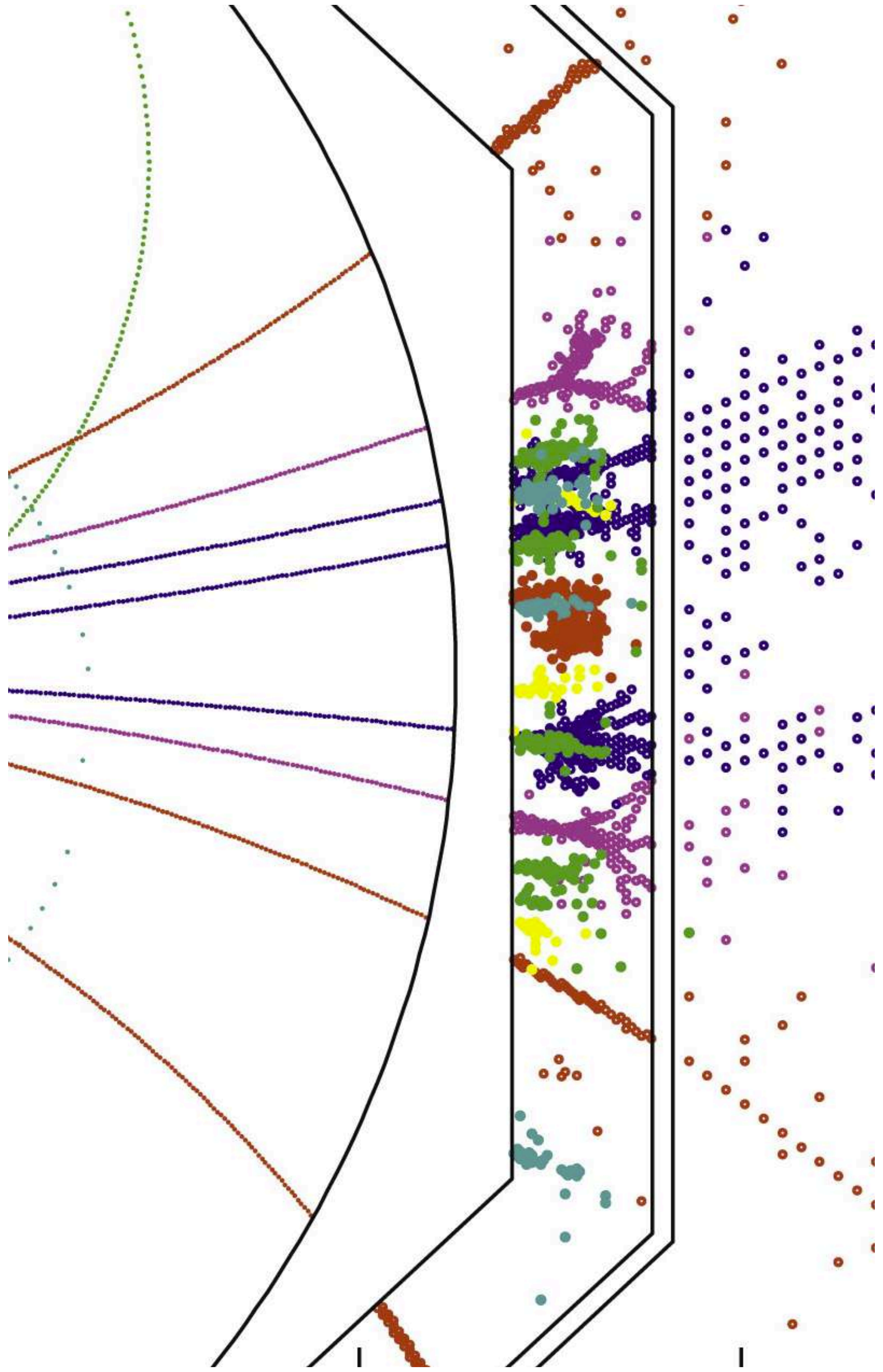
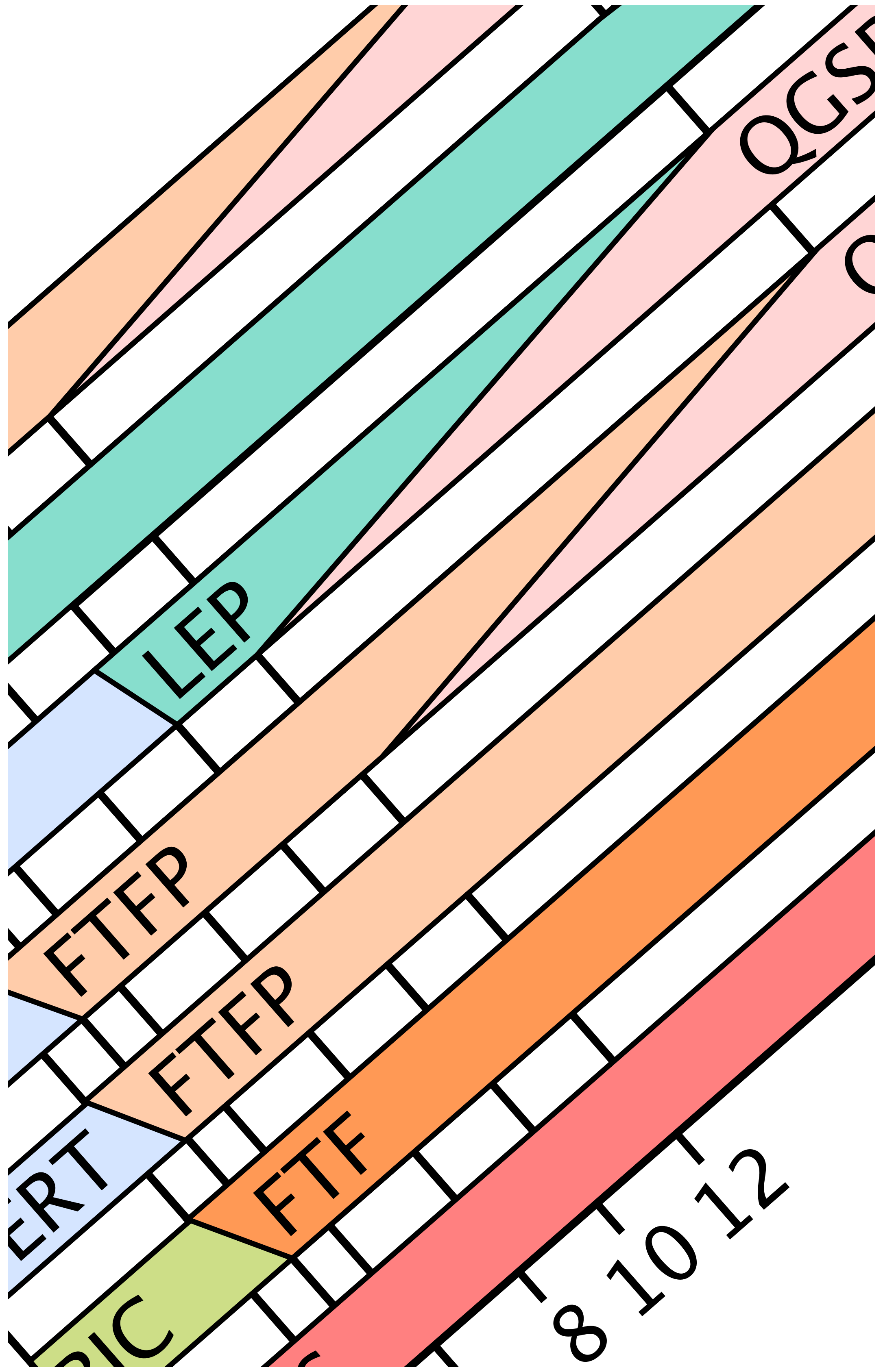




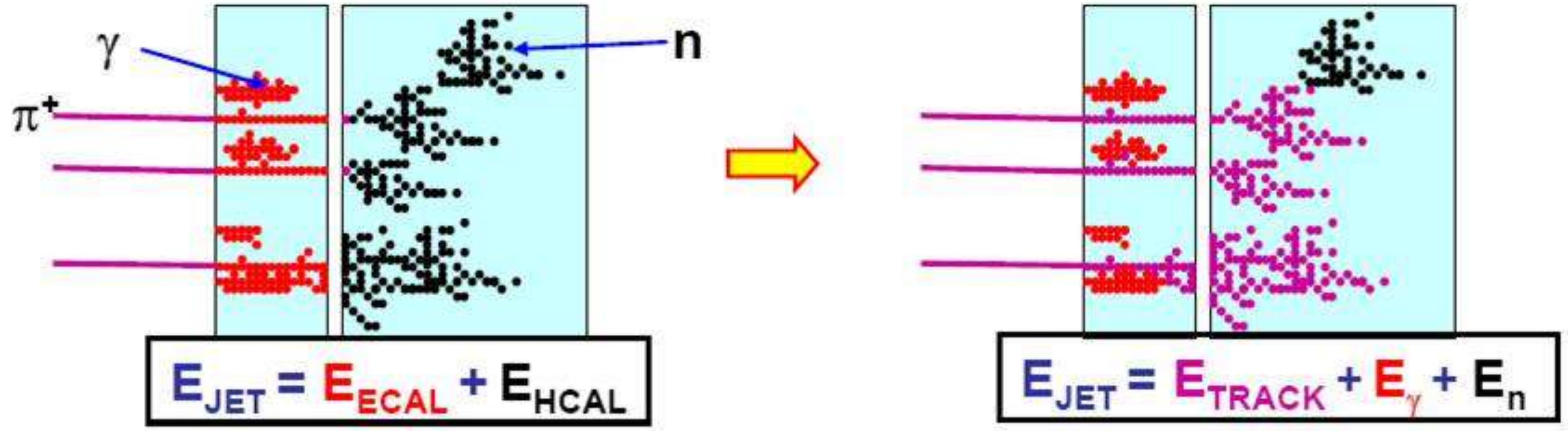


Particle Flow Calorimetry

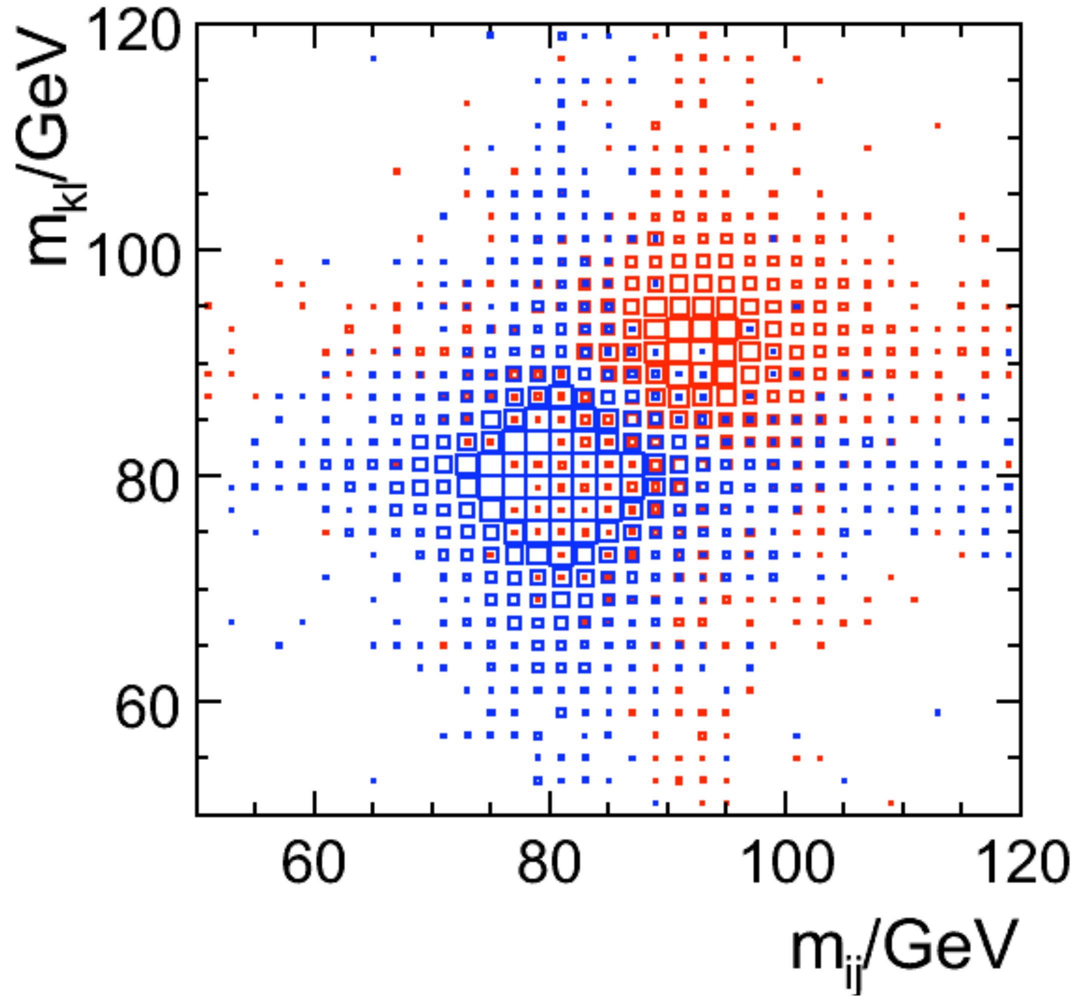
for Best Jet Energy Reconstruction

- **Physics with jets at future e^+e^- collider experiments requires unprecedented jet energy resolution of 3-4%**
- **Particle Flow Algorithm (PFA)**
  - Measurements with best suited detectors depending on particle type
    - Charged particles → tracker
    - Photon → ECAL
    - Neutral hadrons → HCAL
  - PFA requires reconstruction of all visible particles in a jet with
    - **Highly granular calorimeters**
    - High precision tracker

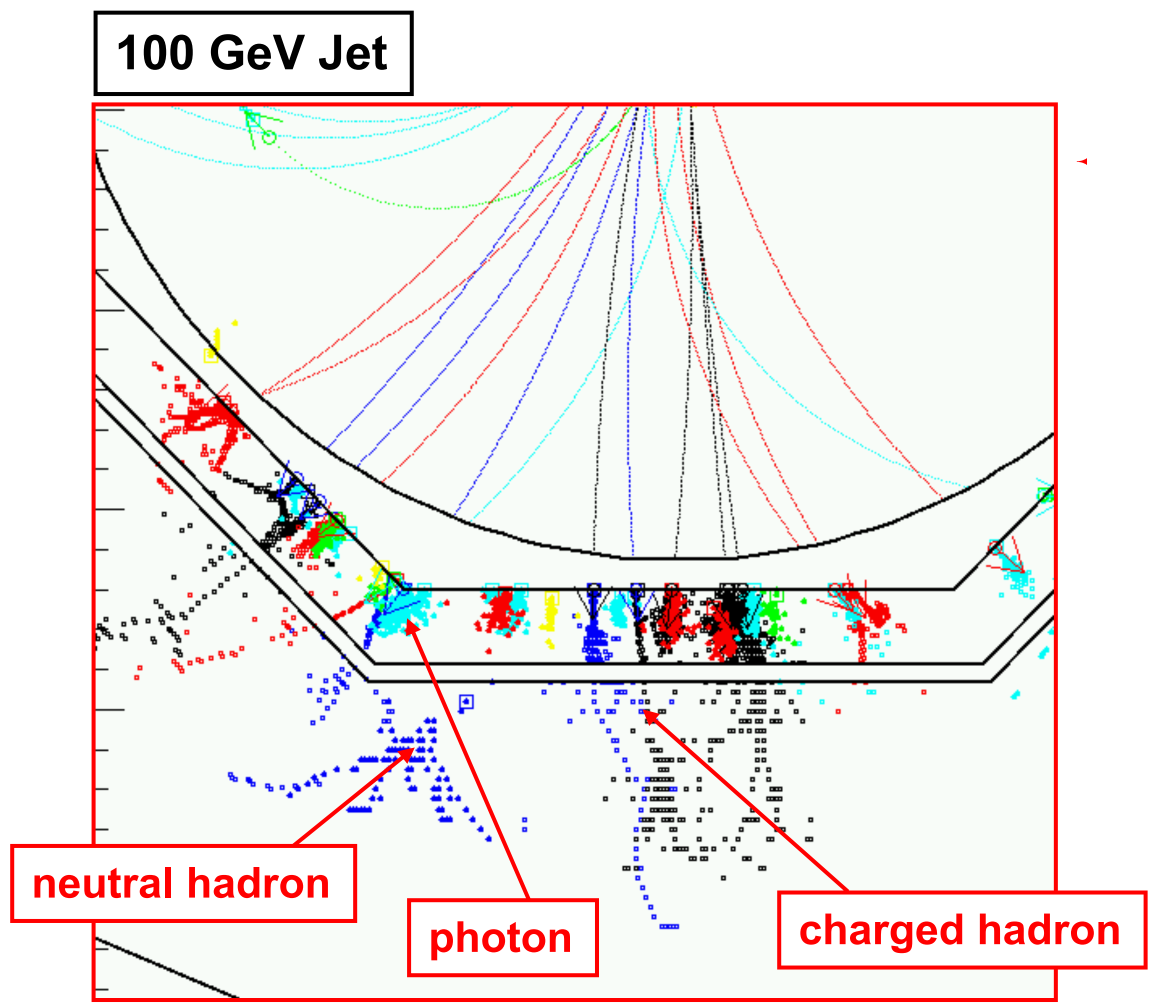
Conventional calorimetry ***Particle flow calorimetry***



Separation of W/Z hadronic decay

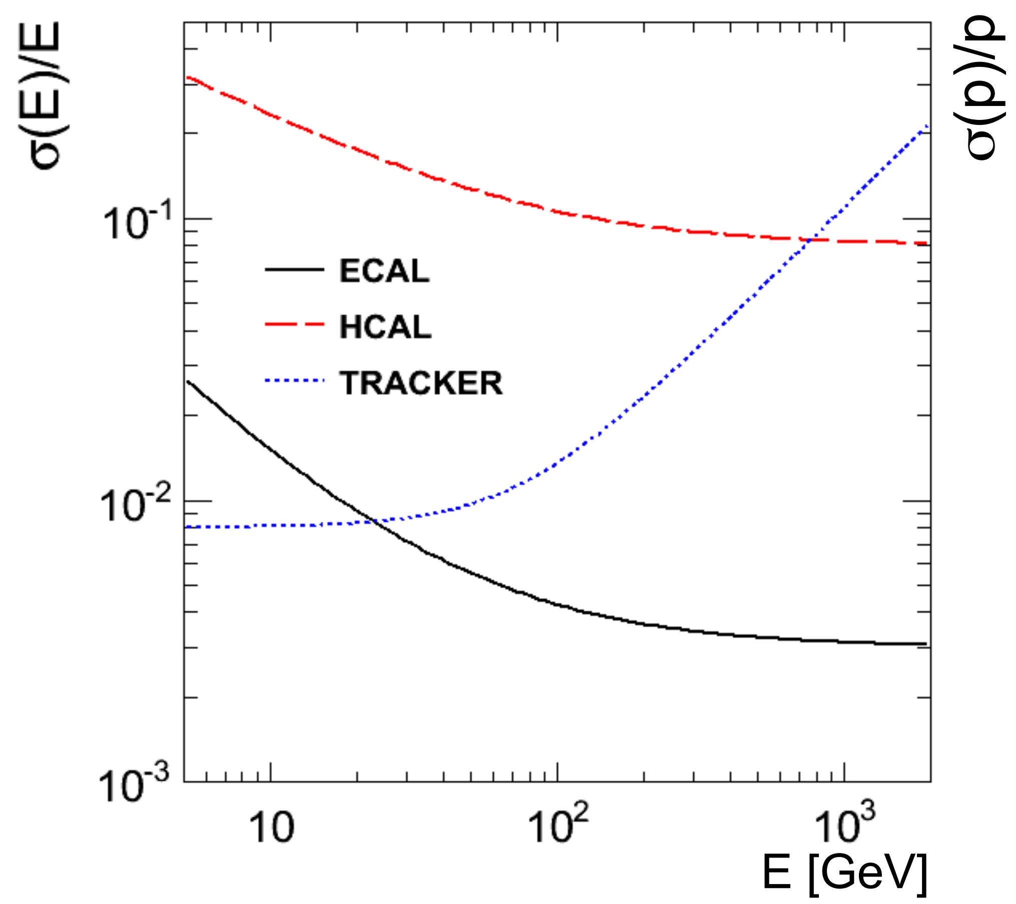


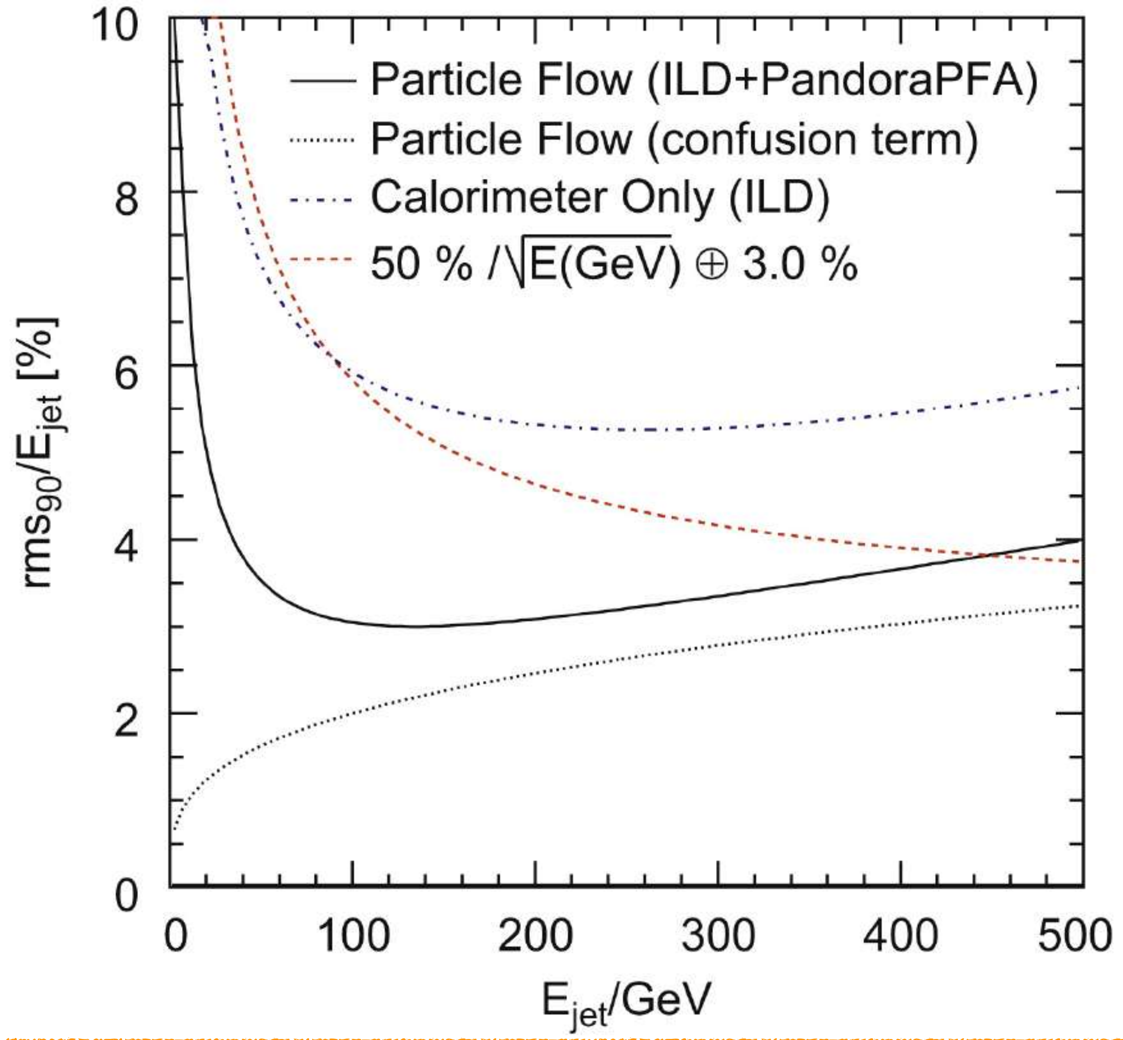
Particle flow reconstruction



Nucl.Instrum.Meth. A611 (2009) 25-40

Performance of subdetectors



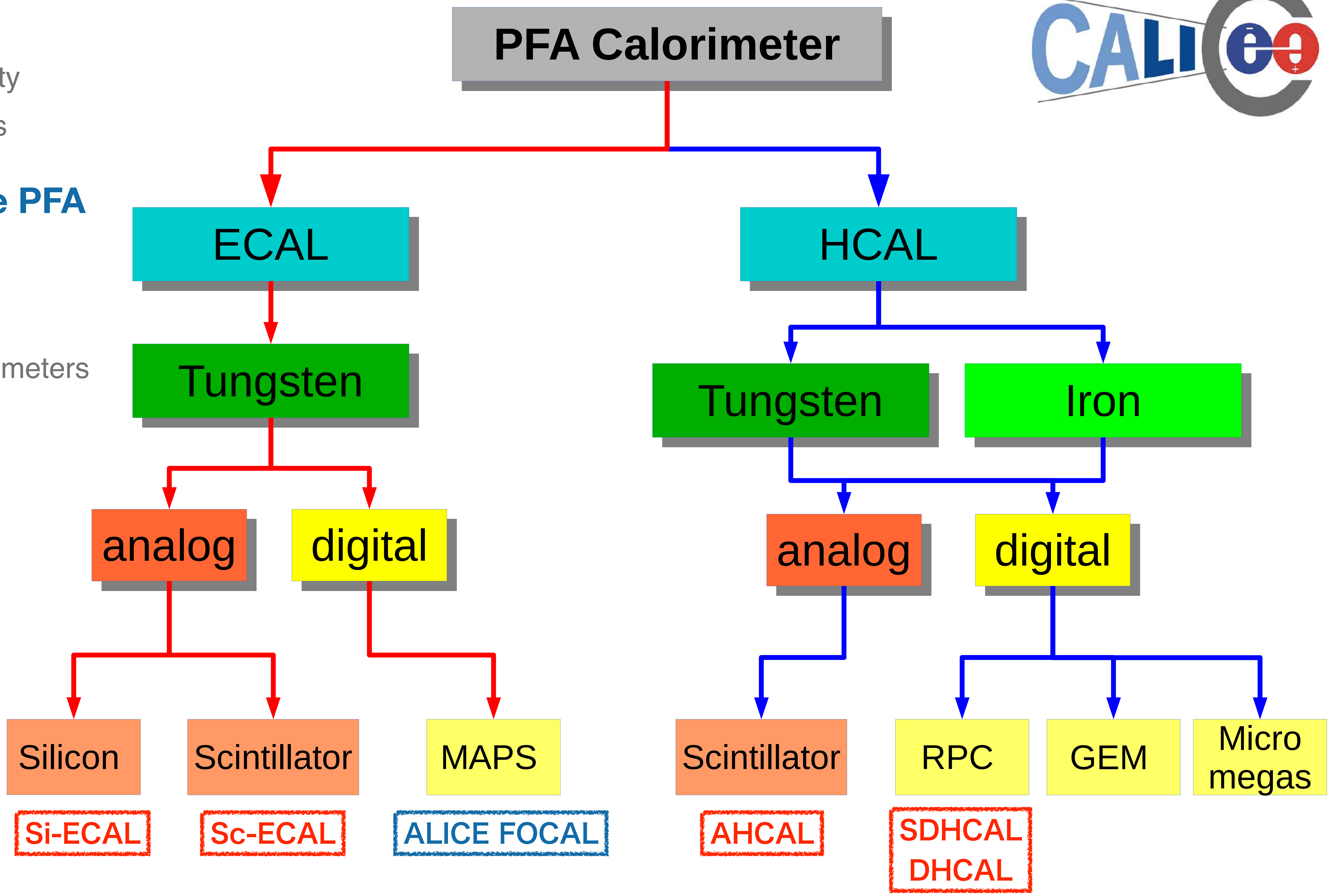


3-4% jet energy resolutions!

CALICE Highly Granular Calorimeters

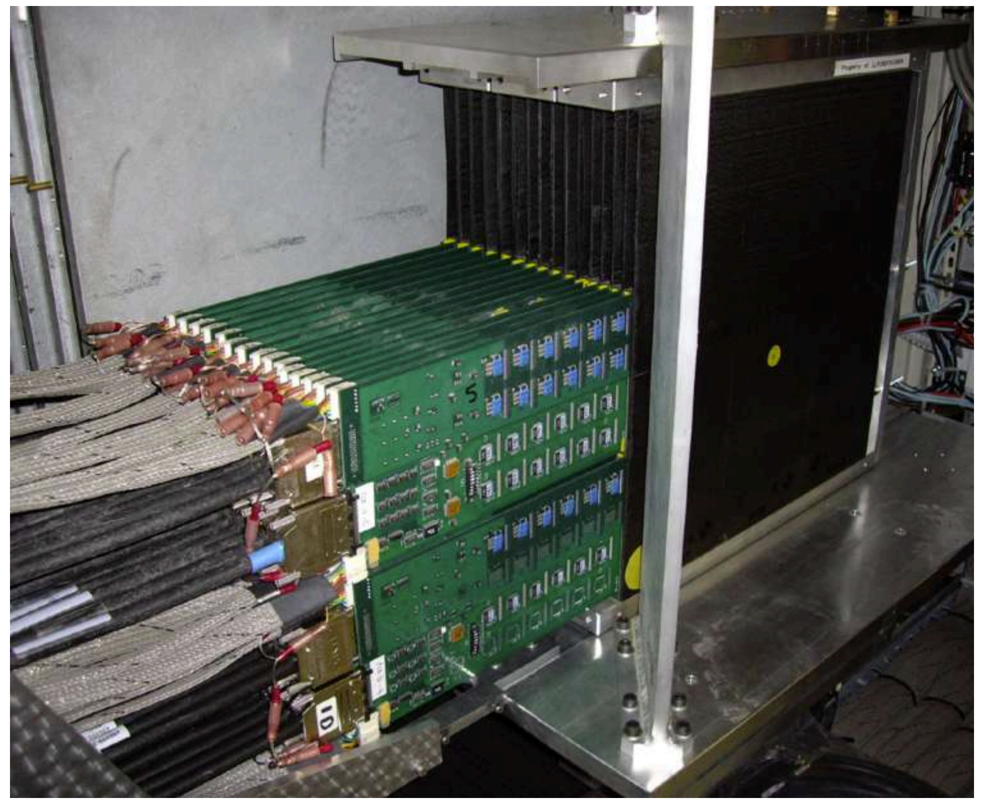
for PFA-baed Calorimetry

- **Goal of CALICE collaboration**
  - Development of PFA-based high granularity calorimeters for future collider experiments
- **Several technology options to realise PFA calorimeters**
  - See previous talk by V. Boudry(#625) for technical implementation of CALICE calorimeters



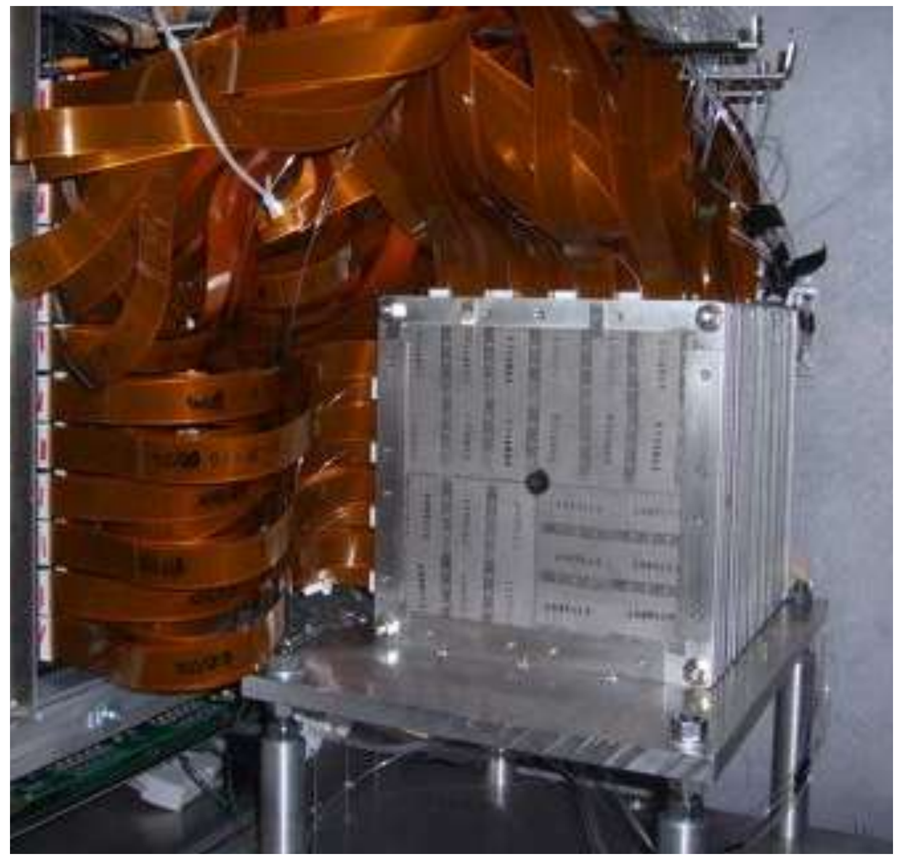
CALICE Highly Granular Calorimeters

Test Beam Prototypes



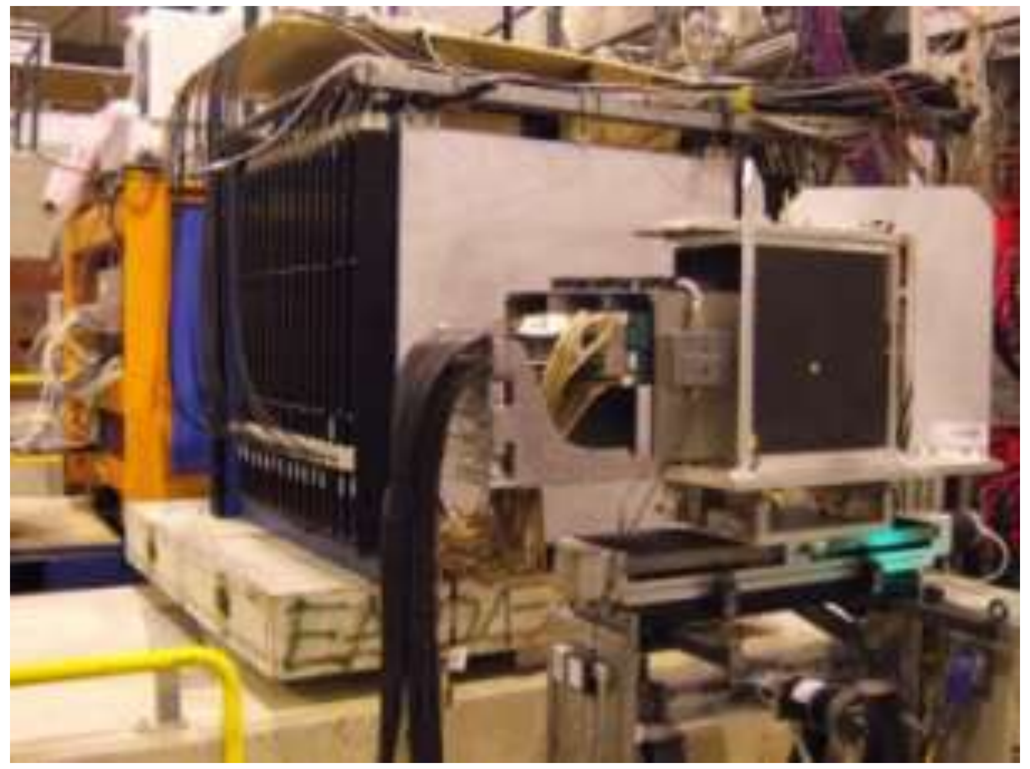
SiW-ECAL

- **Si-sensor** (10000 cells (1×1cm² each))
- **Analogue readout**
- Tungsten absorber
- 30 layers (24X_0, 1λ)



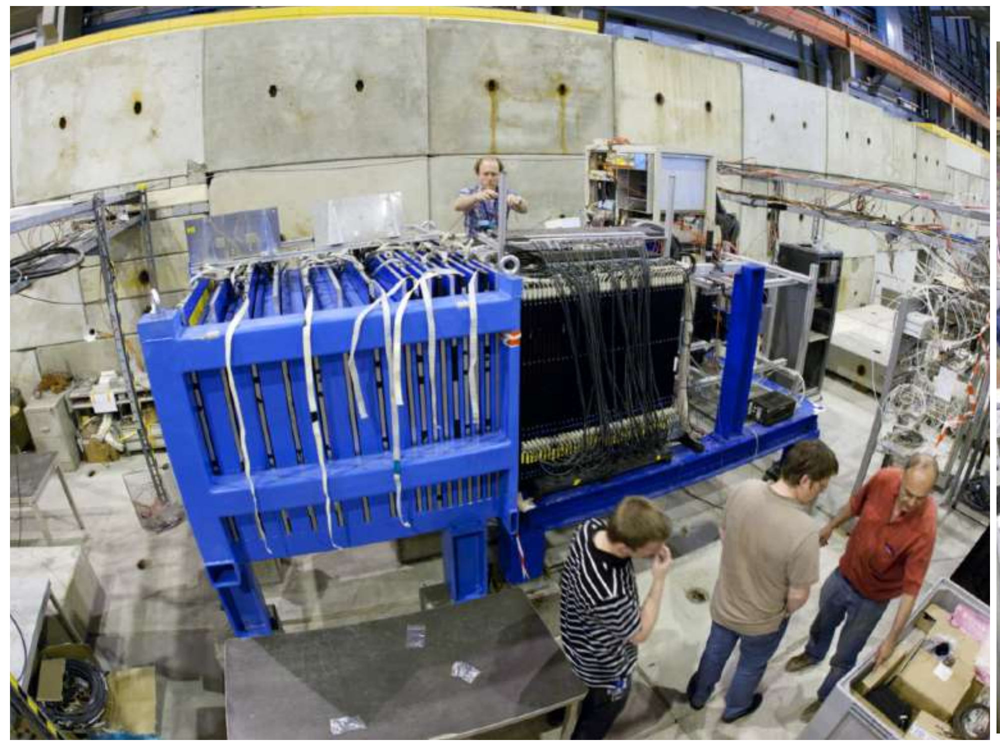
ScW-ECAL

- **Scintillator strips** (1×5cm² each))
- **Analogue readout**
- Tungsten absorber
- 30 layers (24X_0, 1λ)



AHCAL

- **Scintillator tiles** (3×3, 6×6, 12×12 cm², 7608 ch)
- **Analogue readout**
- Steel or Tungsten absorber
- 38 layers (5.3λ)



DHCAL **SDHCAL**

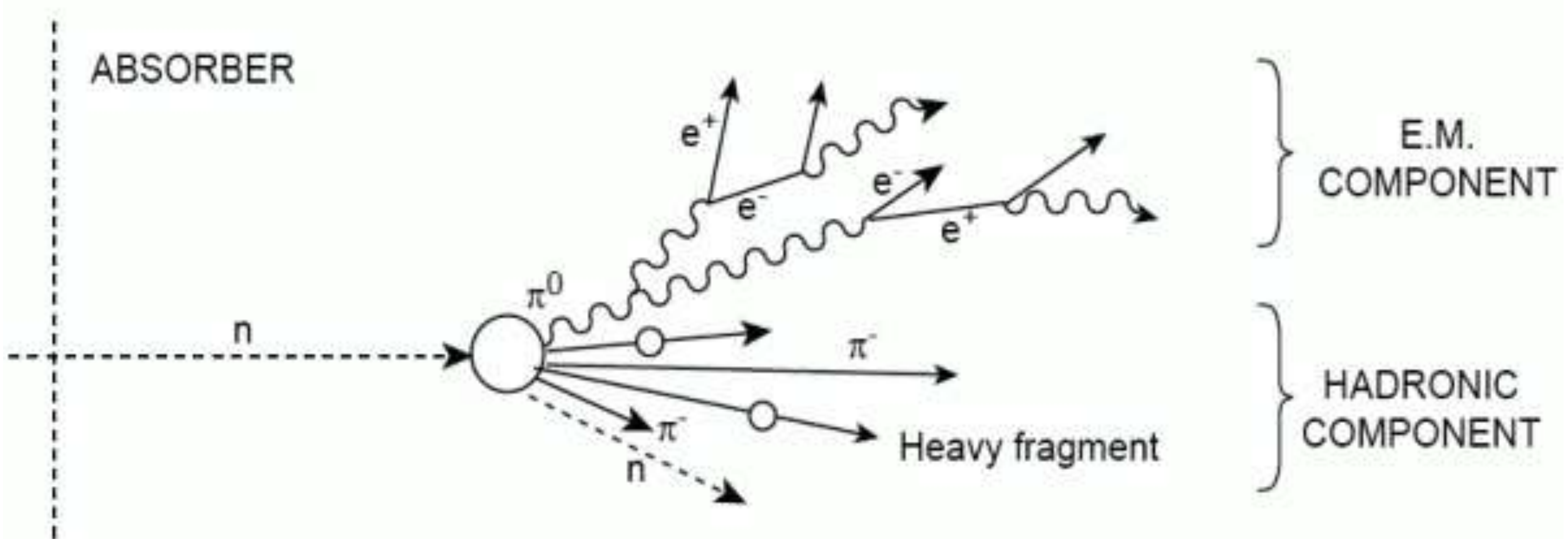
- **GRPC** (up to 500000 cells (1×1cm² each))
- **Digital (1bit) or semi-digital (2bit, multi-threshold) readout**
- Steel or Tungsten absorber
- Up to 48 layers (~6λ)

- **Physics prototypes**
  - Full-layer test beam prototypes for proof-of-principle of high-granularity calorimeter concept
- **Technological prototypes**
  - Demonstrate good performance with more "realistic" implementation (embedded electronics, power pulsing, mechanical structure,…)
  - For recent progresses, see previous talk by V. Boudry(#625)

Hadronic Shower

Why It Matters?

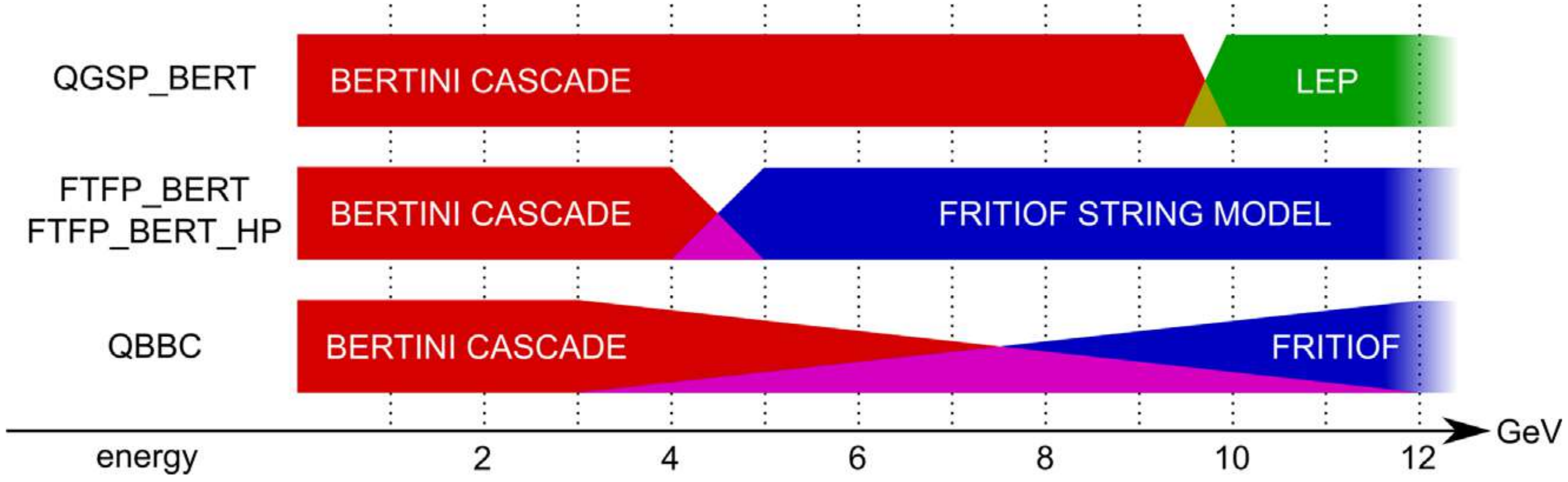
- **Hadronic showers are quite complex**
  - Initiated by hard collision of incident hadron with a nucleus
  - Narrow core of electromagnetic cascades by photons from π^0/η^0
  - Surrounding halo dominated by charged hadrons
  - Large event-by-event fluctuation of electromagnetic and hadronic components ratio
  - Invisible energies as nuclear binding energy, nuclear recoil, late component
    → **limited hadronic energy resolution**



- **Correct understanding hadronic shower is crucial**

- **GEANT4 hadronic shower model**
  - Modelling of hadronic shower @GEANT4 is not perfect
  - CALICE test beam data to validate GEATN4 shower model

Studies on hadronic showers using test beam data with prototypes of CALICE high-granularity calorimeters will be presented in this talk



Hadronic Shower Studies

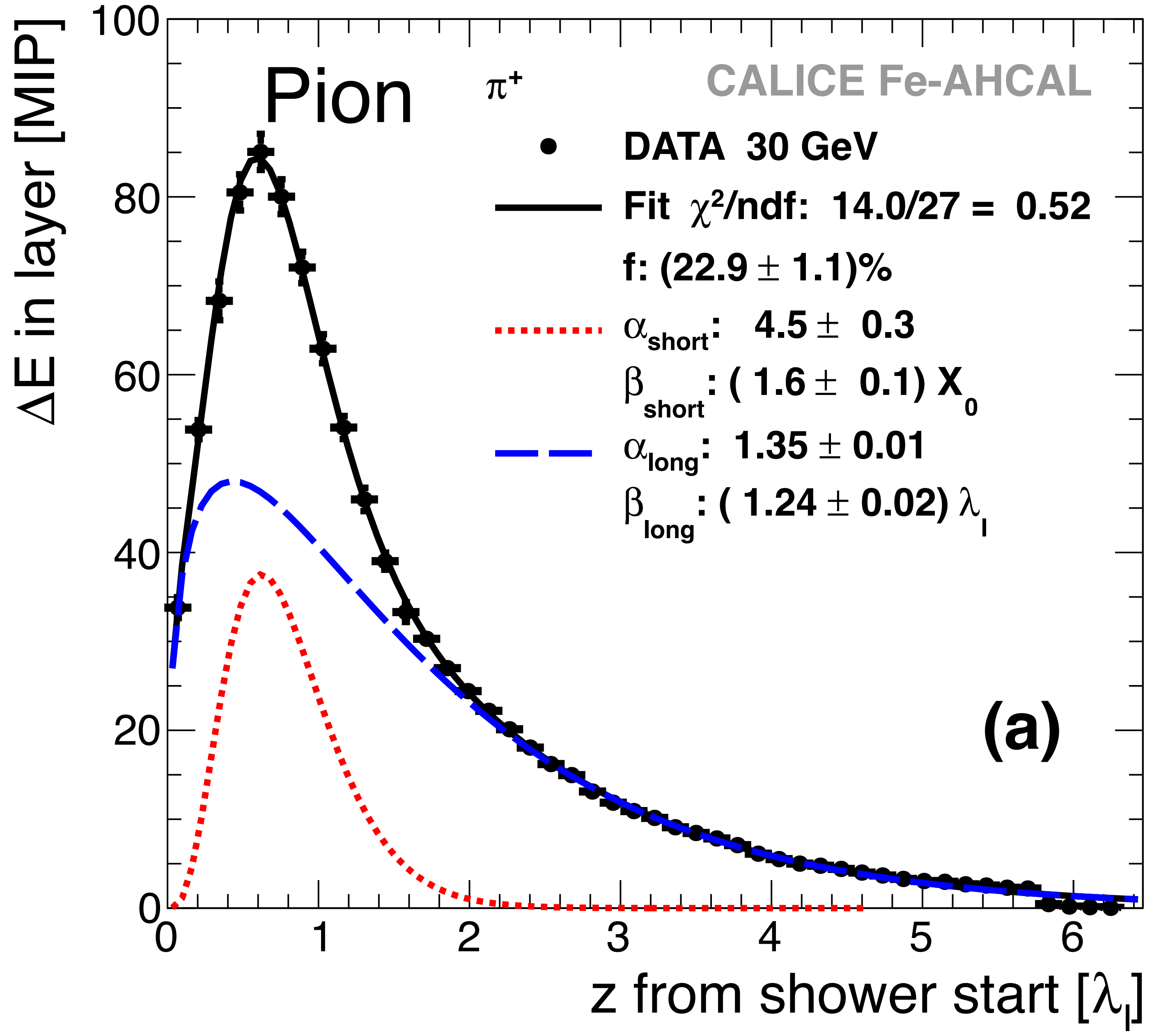
JINST 11(2016)P06013

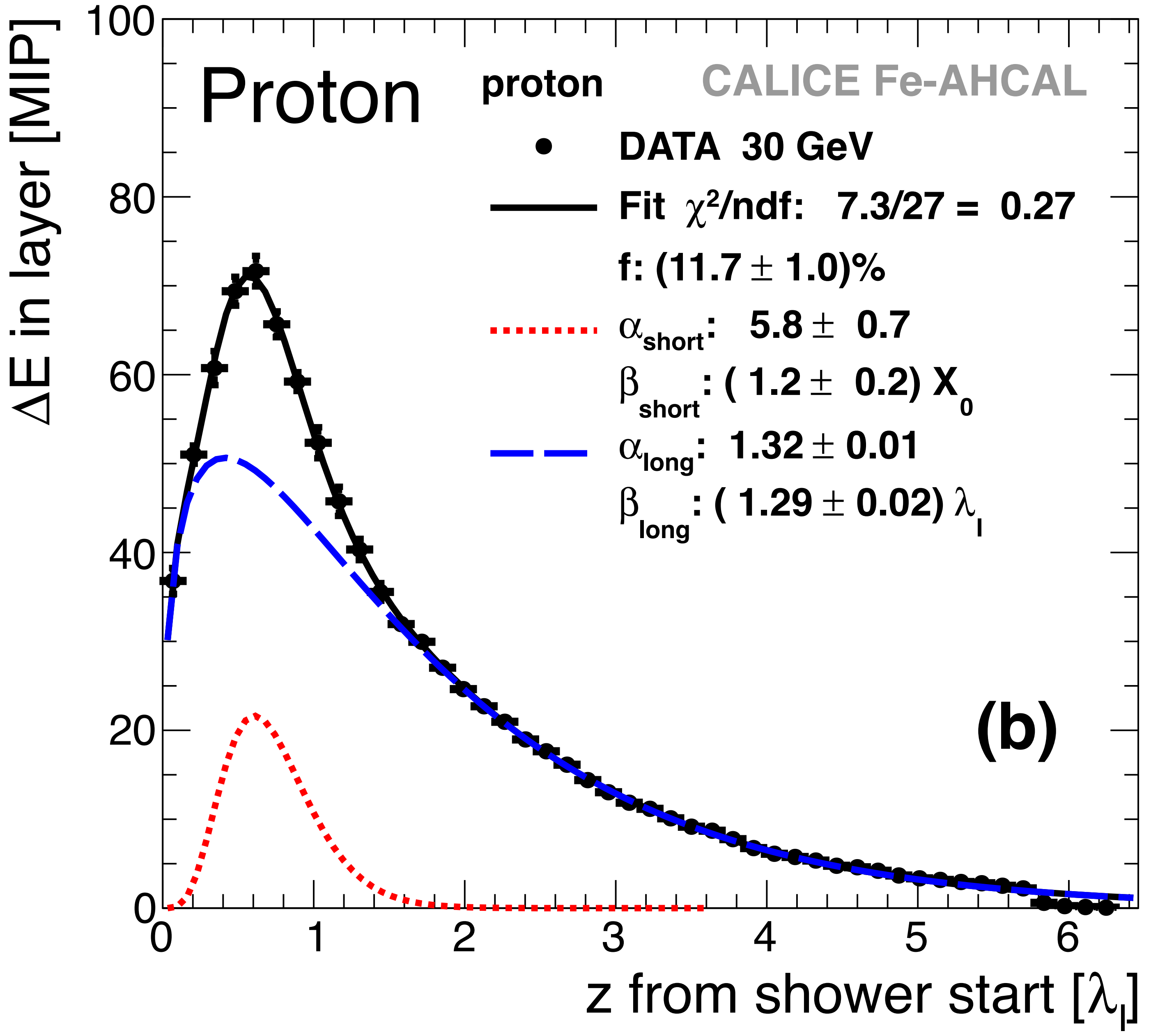
AHCAL

- **Longitudinal shower profile measured by AHCAL**
  - Test beam data: positive pion and proton 10-80GeV@CERN and FNAL
  - Decompose shower components
    - Short component: electromagnetic component
    - Long component: hadronic component
  - Extract ratio of hadronic to electromagnetic response (h/e)

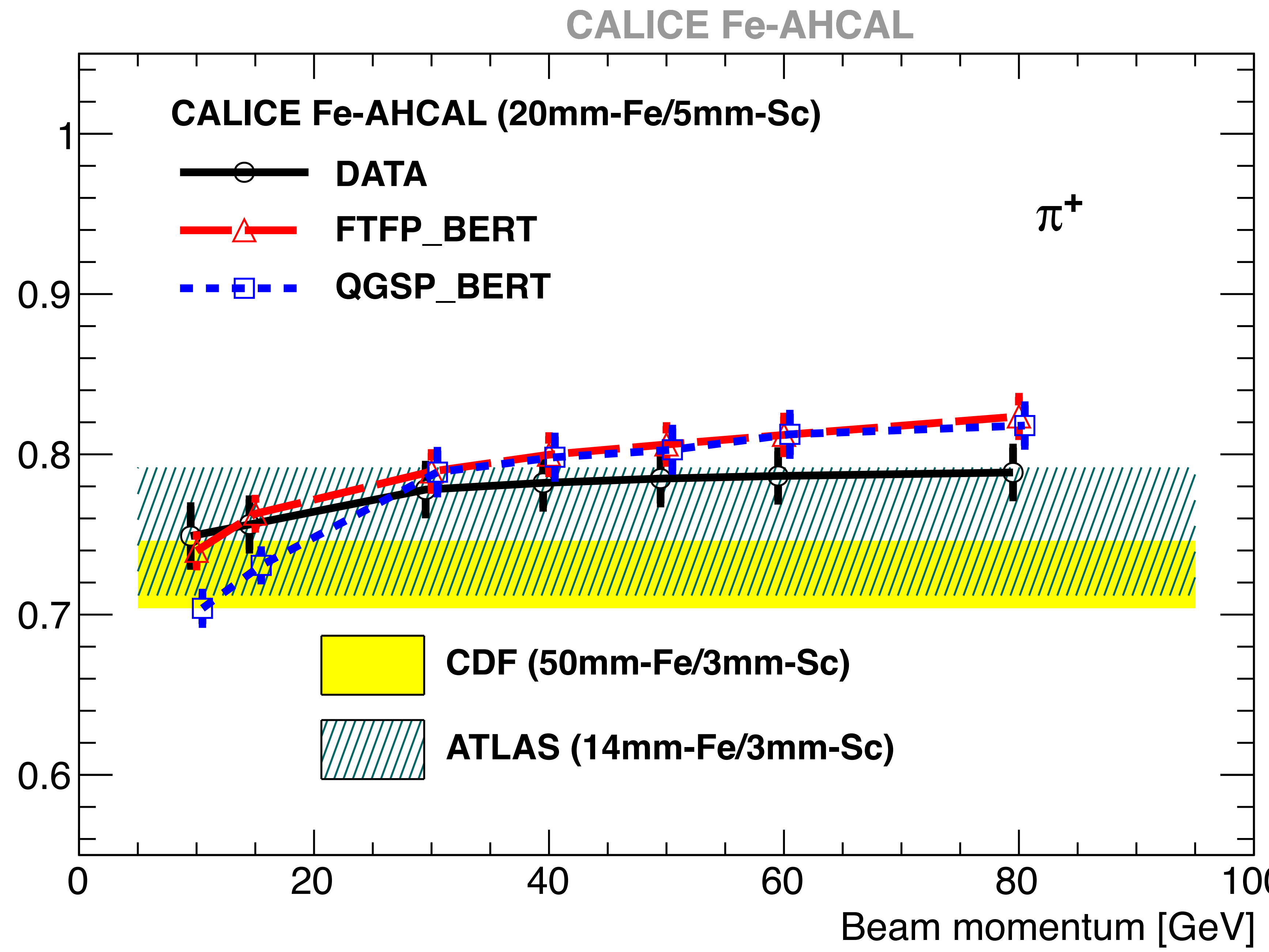
$$\Delta E(z) = A \cdot \left\{ \frac{f}{\Gamma(\alpha_{\mathrm{short}})} \cdot \left(\frac{z}{\beta_{\mathrm{short}}}\right)^{\alpha_{\mathrm{short}}-1} \cdot \frac{e^{-z/\beta_{\mathrm{short}}}}{\beta_{\mathrm{short}}} + \frac{1-f}{\Gamma(\alpha_{\mathrm{long}})} \cdot \left(\frac{z}{\beta_{\mathrm{long}}}\right)^{\alpha_{\mathrm{long}}-1} \cdot \frac{e^{-z/\beta_{\mathrm{long}}}}{\beta_{\mathrm{long}}} \right\}$$

Longitudinal hit energy distribution





Ratio of hadronic to electromagnetic response (h/e)



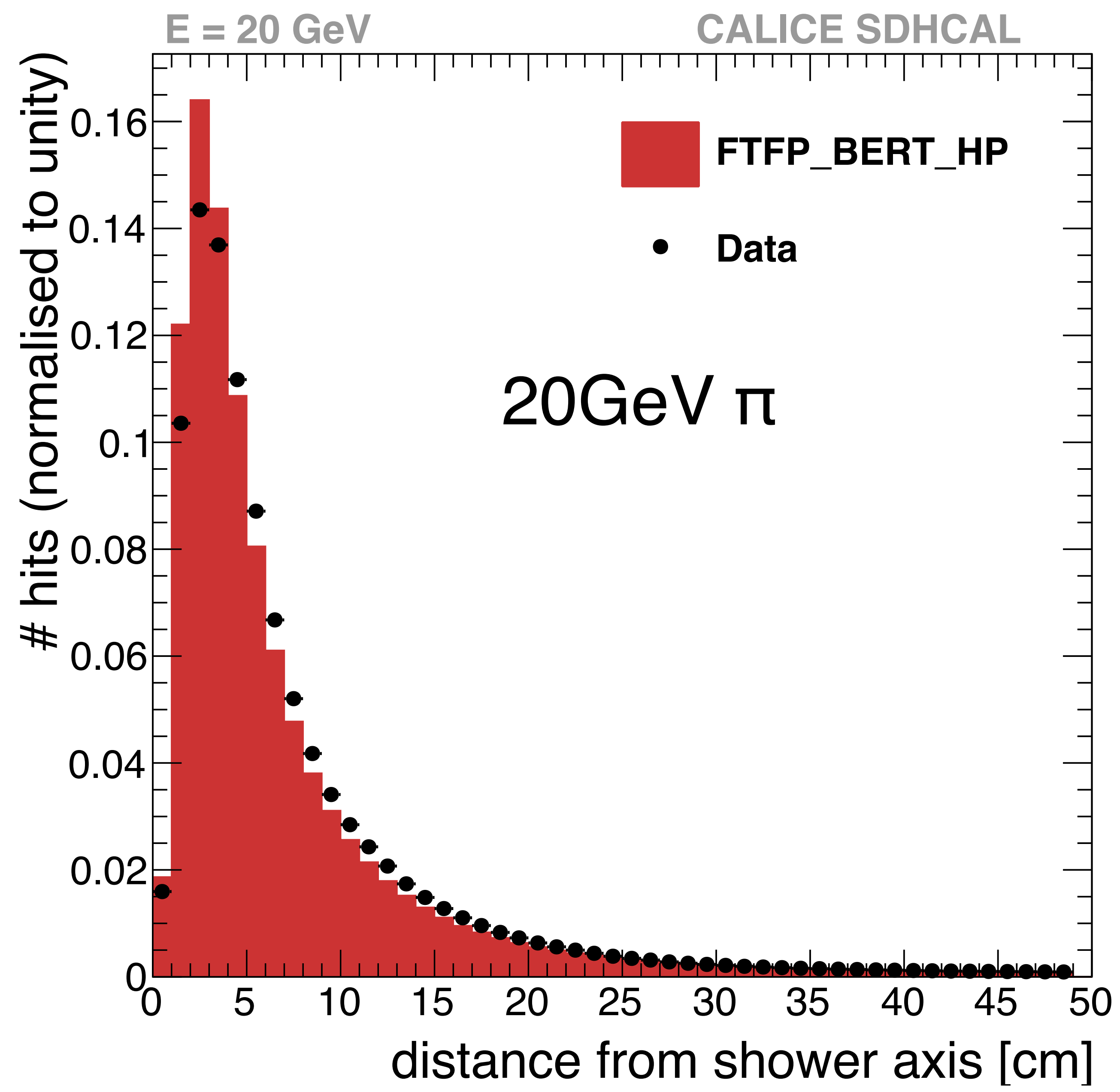
Hadronic Shower Studies

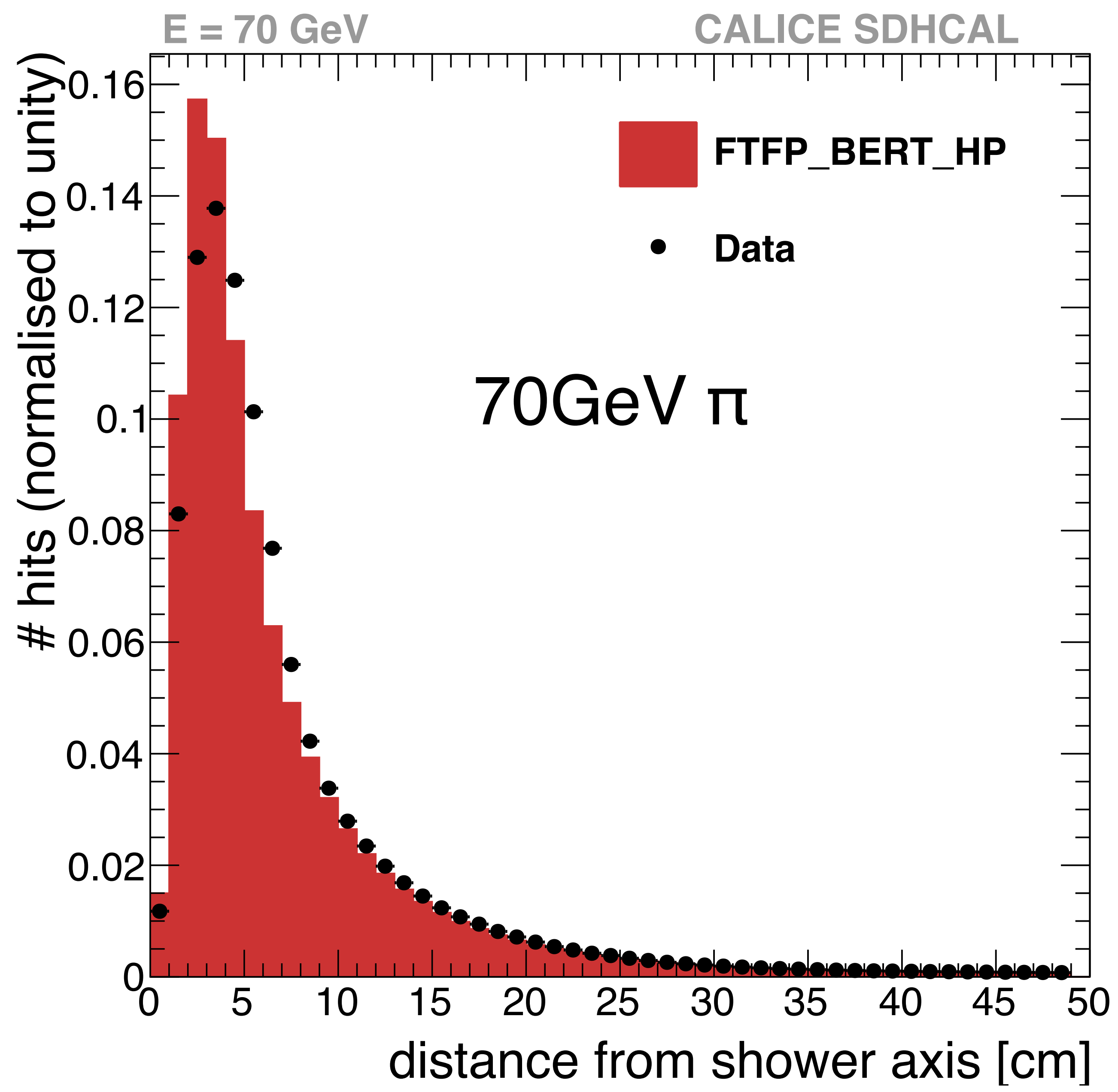
JINST 11(2016)P06014

SDHCAL

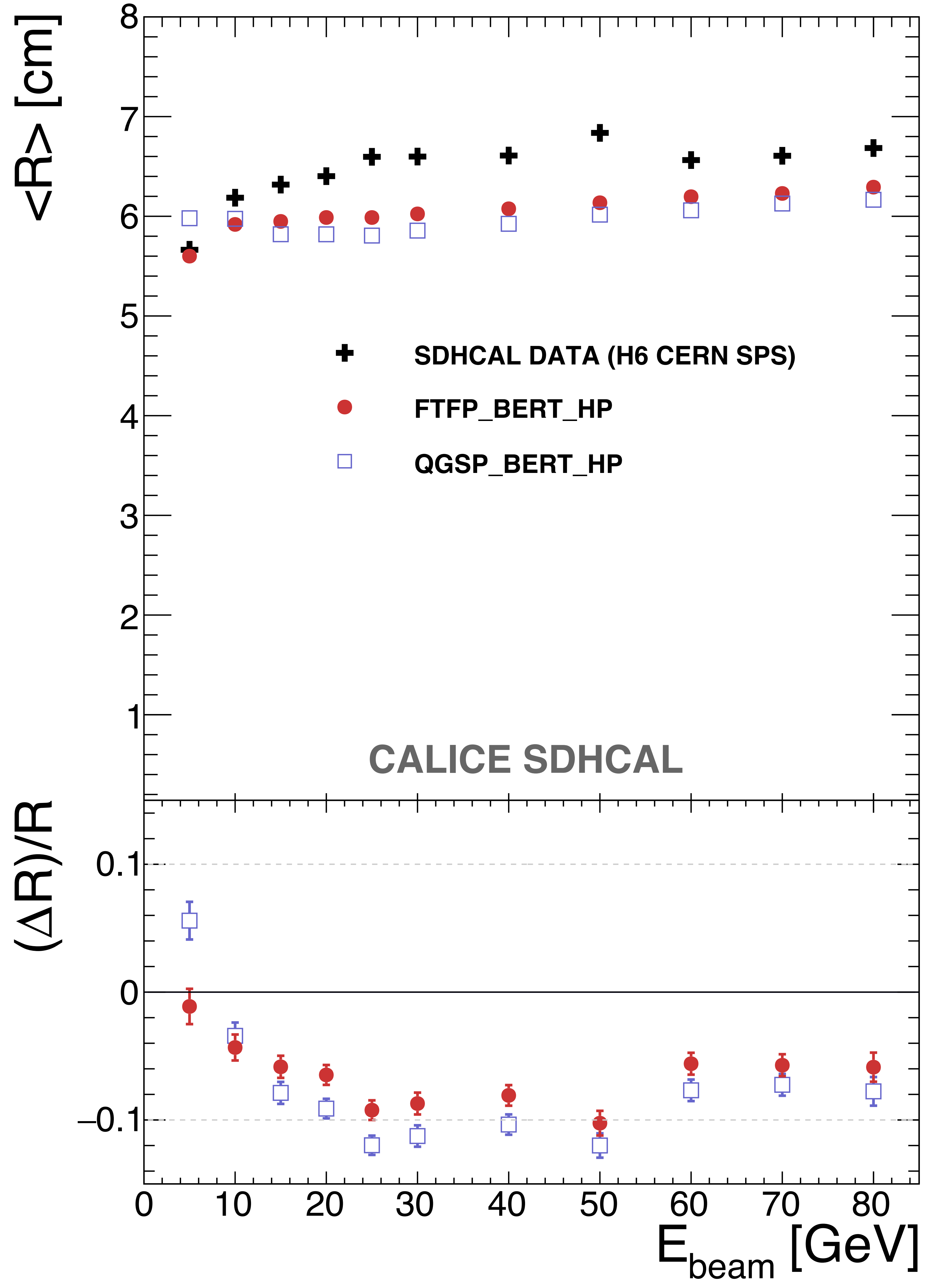
- **Finer transverse segmentation of SDHCAL is useful for radial profile study**
    - Test beam: 5-80GeV pions @CERN SPS
    - Simulation: GEANT4 ver9.6 with High Precision (HP) package
- **Radial profile is narrower in simulation**

Radial hit distribution





Mean of radial distribution



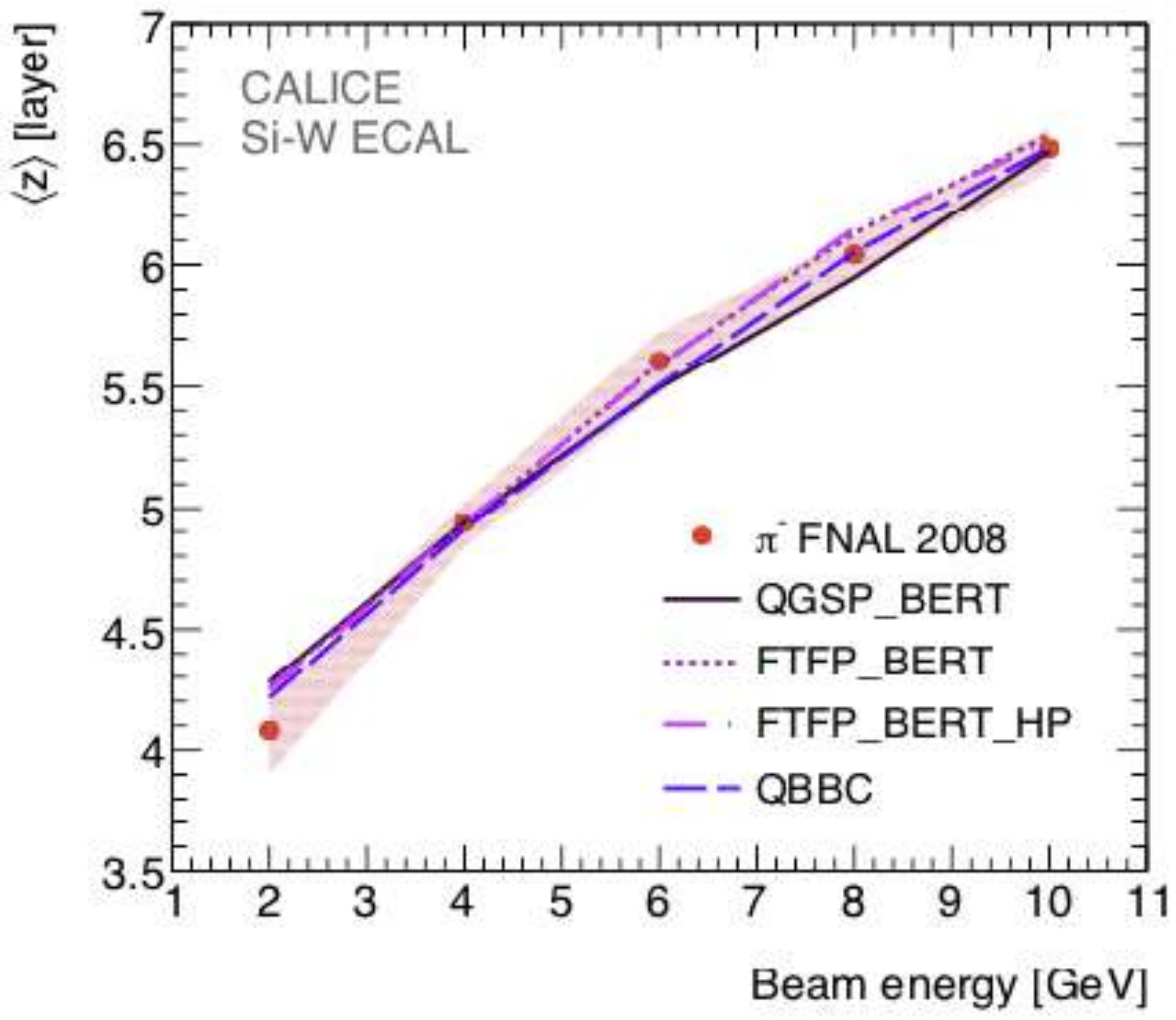
Hadronic Shower Studies

NIM A794 (2015) 240-254

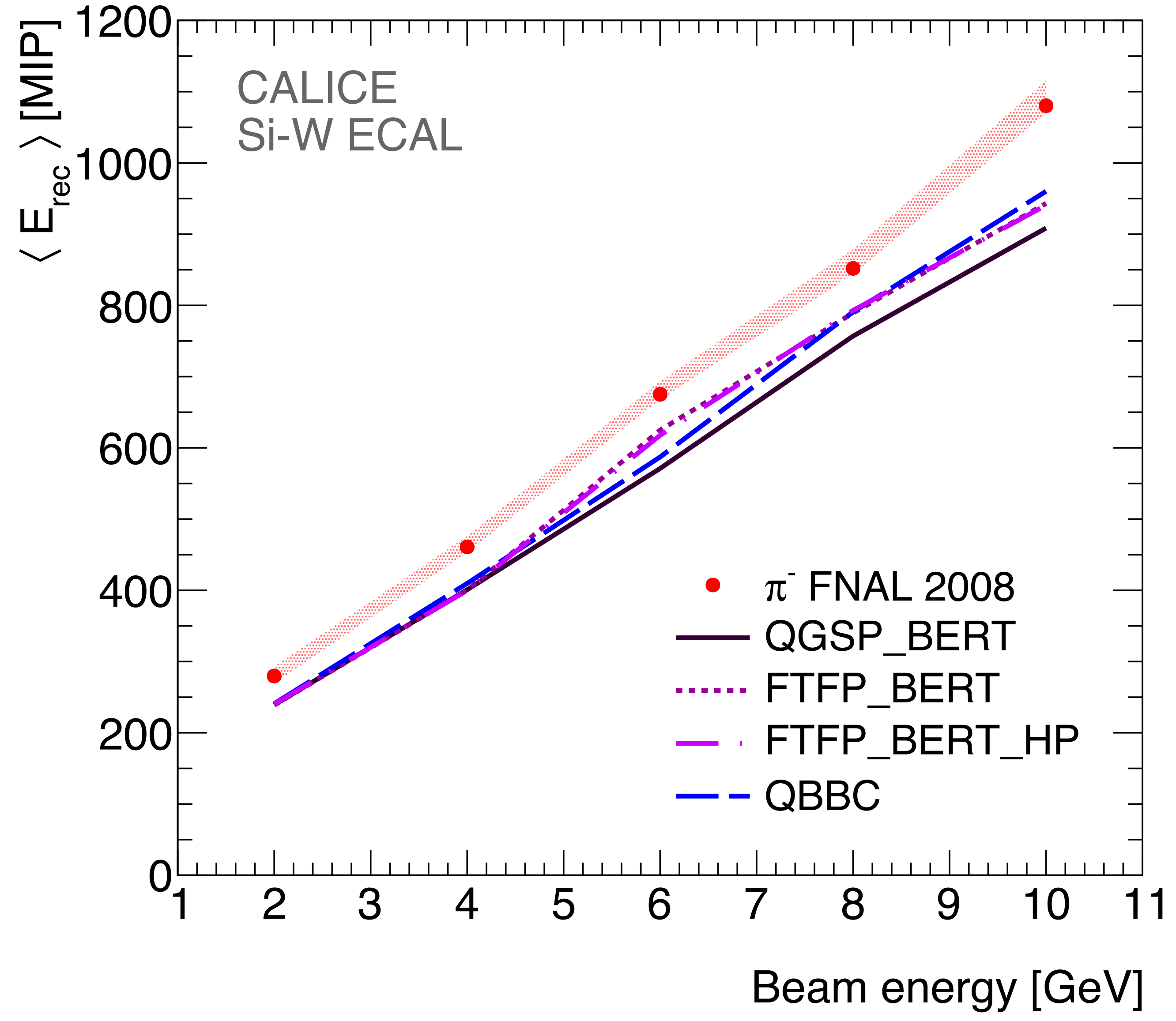
SiW-ECAL

- **Shower studies with low energy hadrons using SiW-ECAL**
    - Test beam: negative pions 2-10GeV @FNAL
- **Comparison with simulation**
    - Agreement to within 20% (much closer for most observables)
    - Longitudinal hit distributions well described
    - Largest discrepancies in longitudinal and radial profile of reconstructed energy

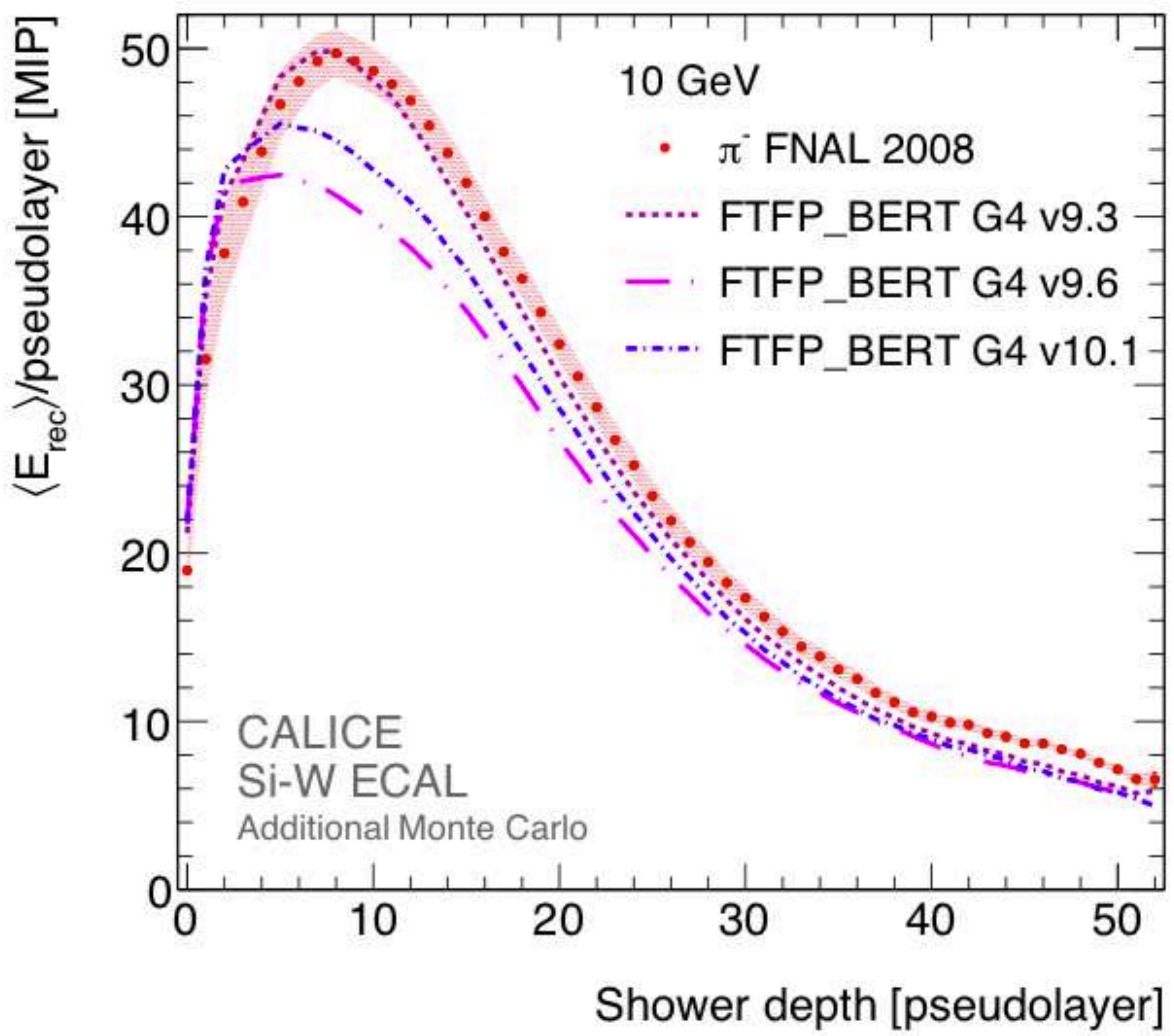
Mean of longitudinal hit distribution



Mean of longitudinal energy distribution



Longitudinal energy distribution (10GeV π⁻)

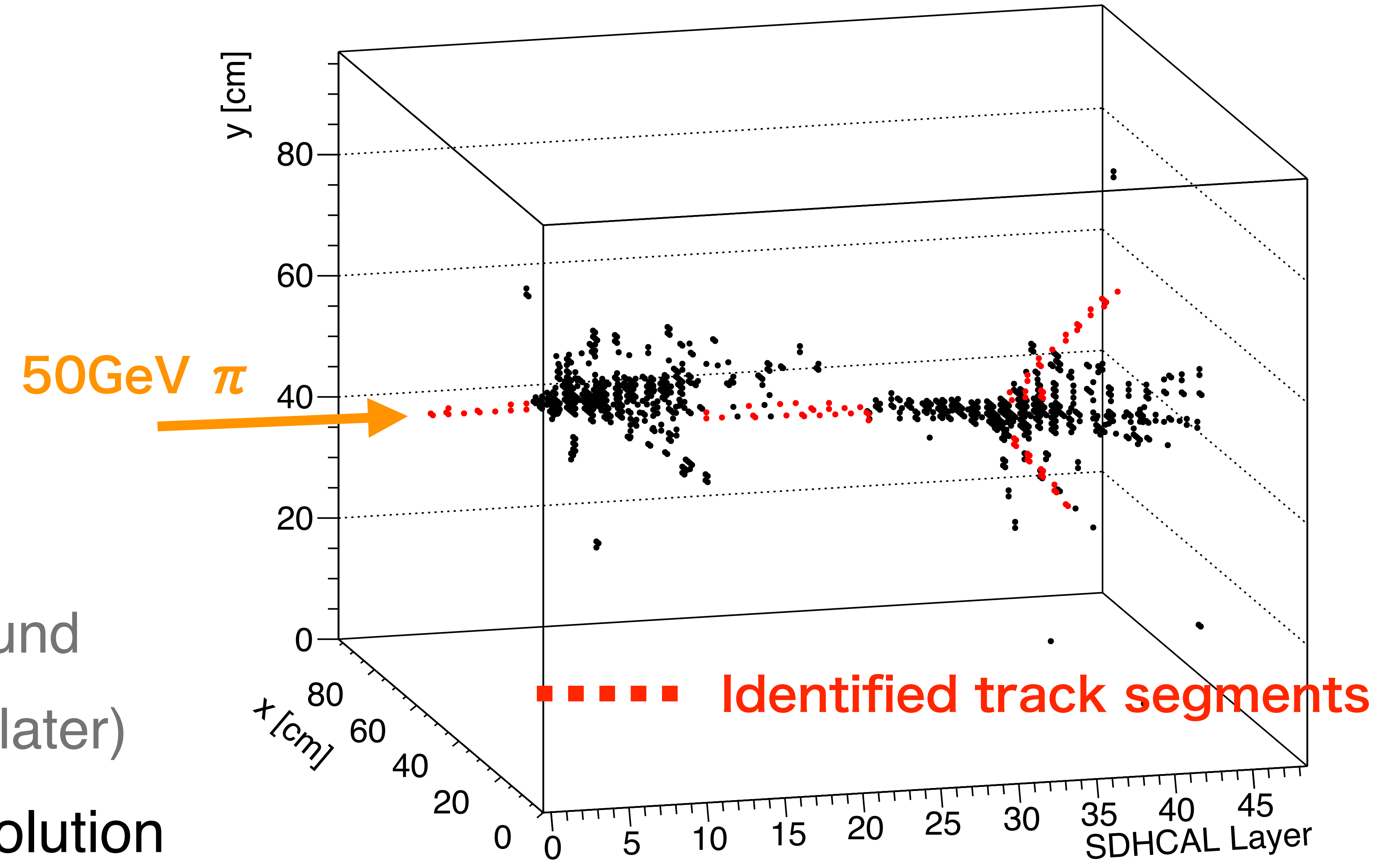


Hadronic Shower Studies

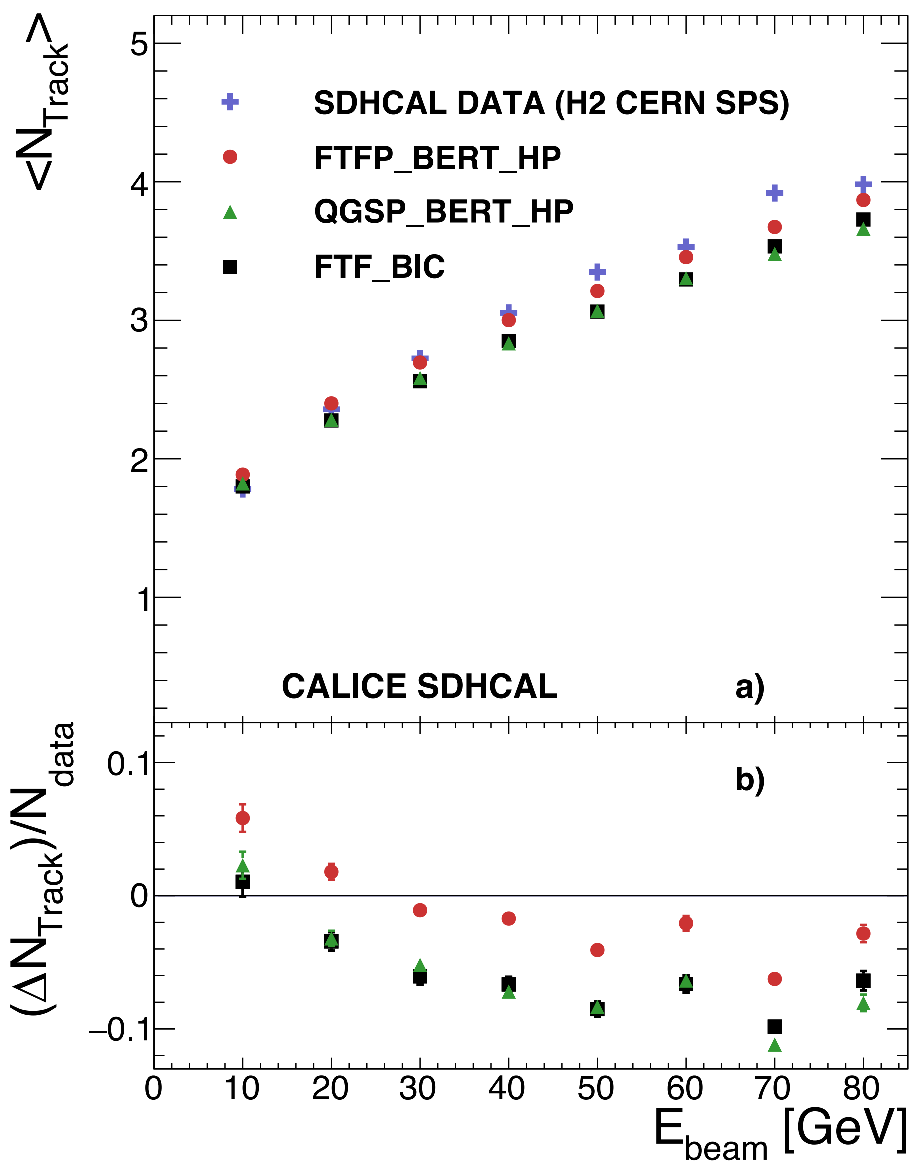
JINST 12(2017)P05009

Track Segments@SDHCAL

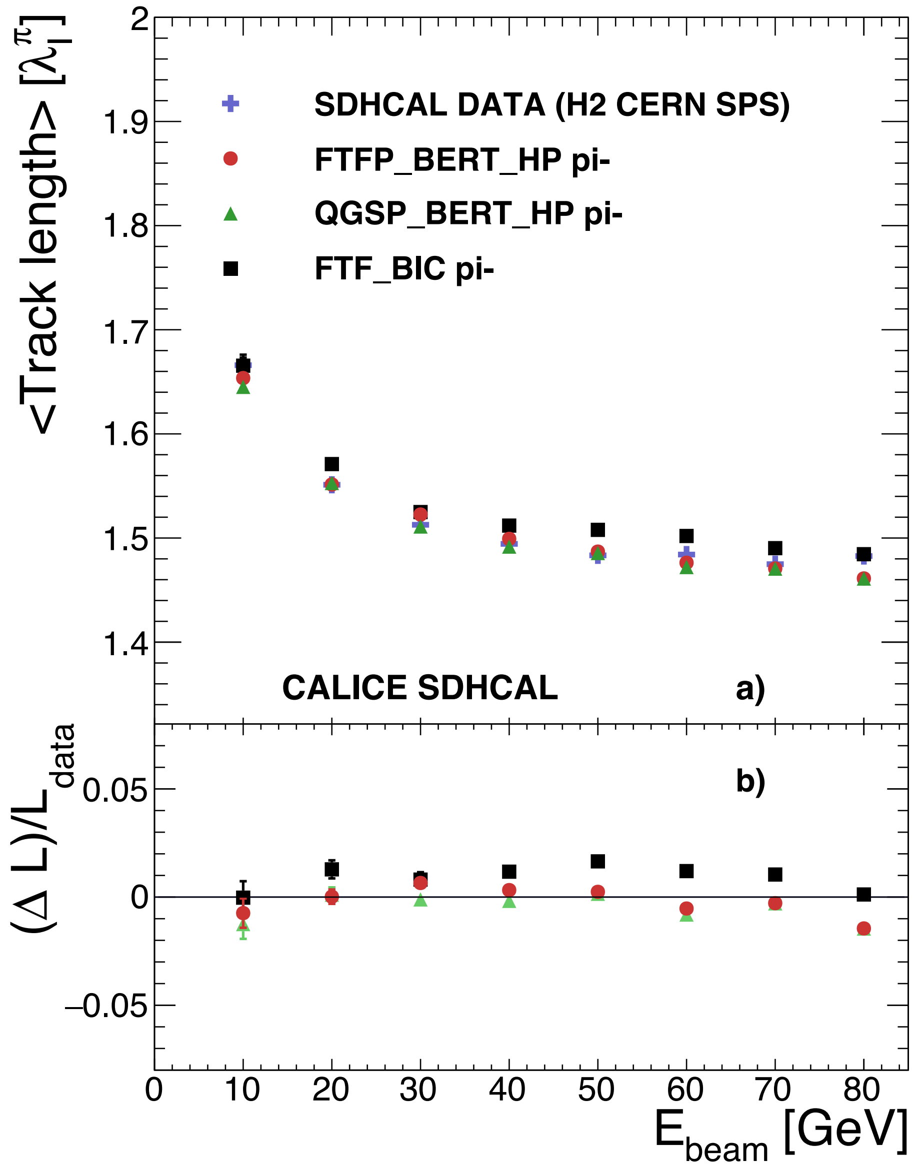
- **Study fine shower structure using track segments**
  - Test beam data: pions 10-80GeV@CERN SPS
- **Track segments found in dense hadronic shower**
  - Track finding based on Hough Transform
  - Useful for detailed shower study, in-situ calibration and better energy reconstruction
  - Slight improvement of energy reconstruction by giving different weight for hits on found tracks irrespective of thresholds (energy reconstruction@SDHCAL to be discussed later)



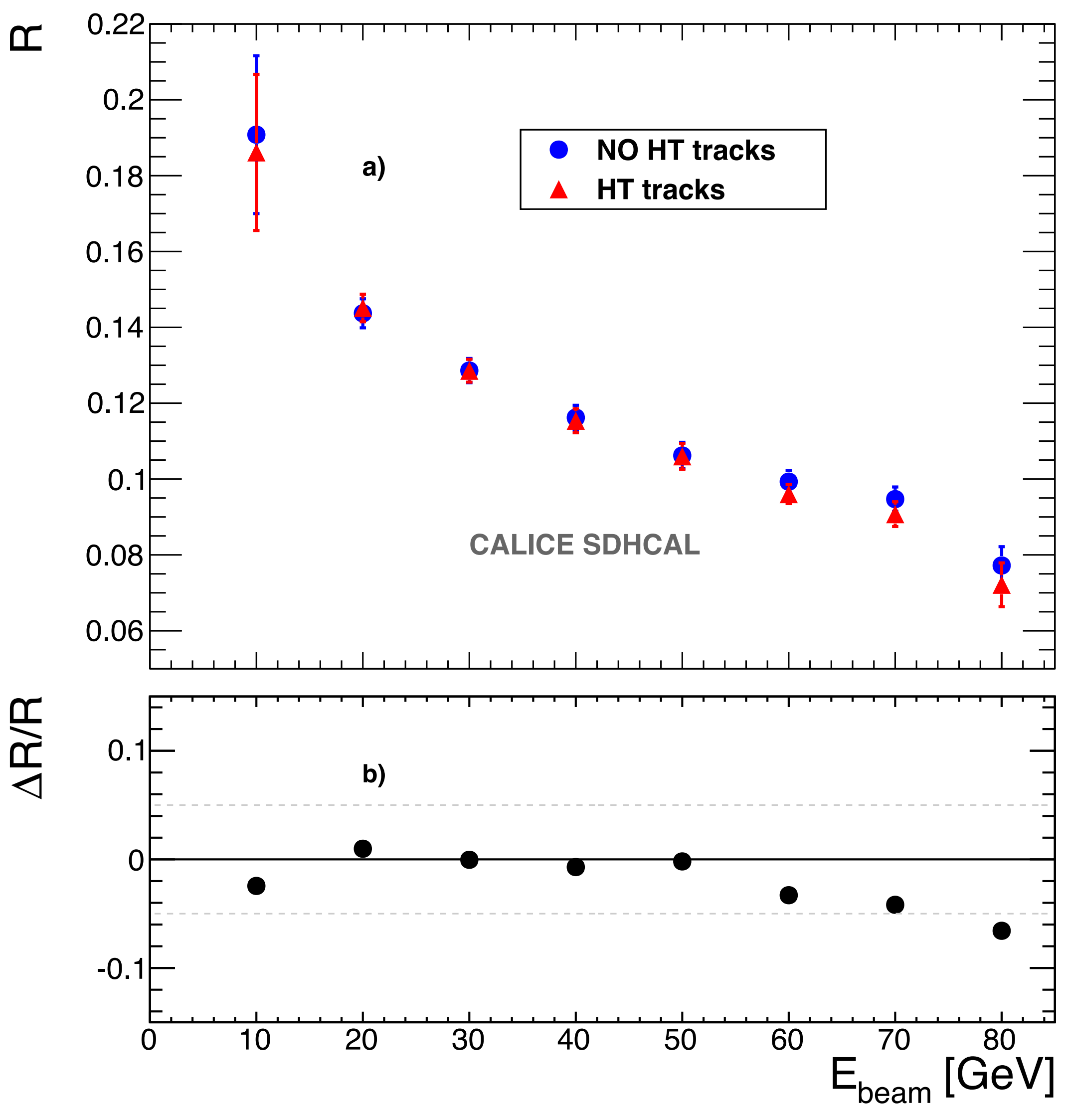
Mean of # tracks



Mean of track length



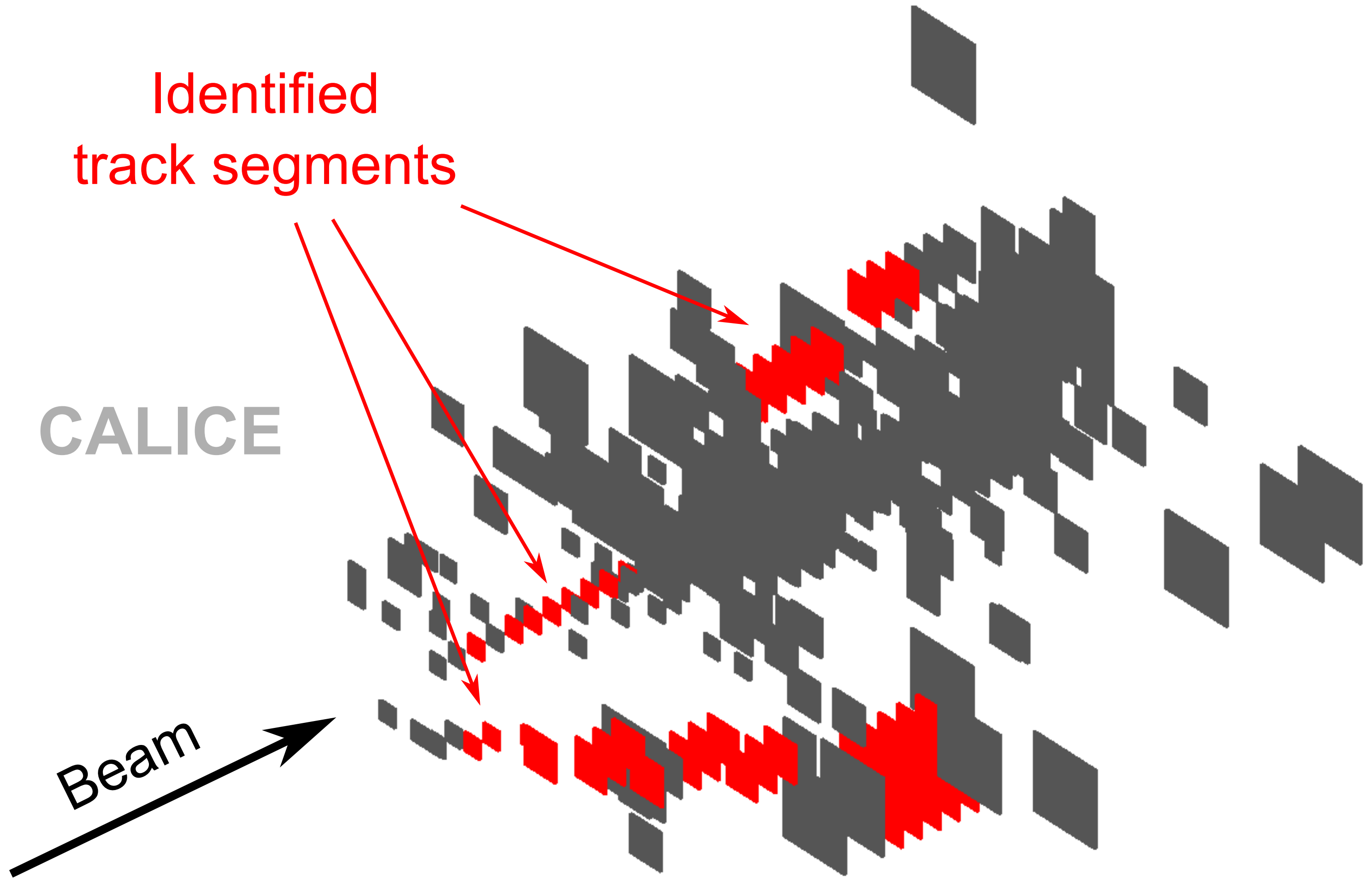
Energy resolution



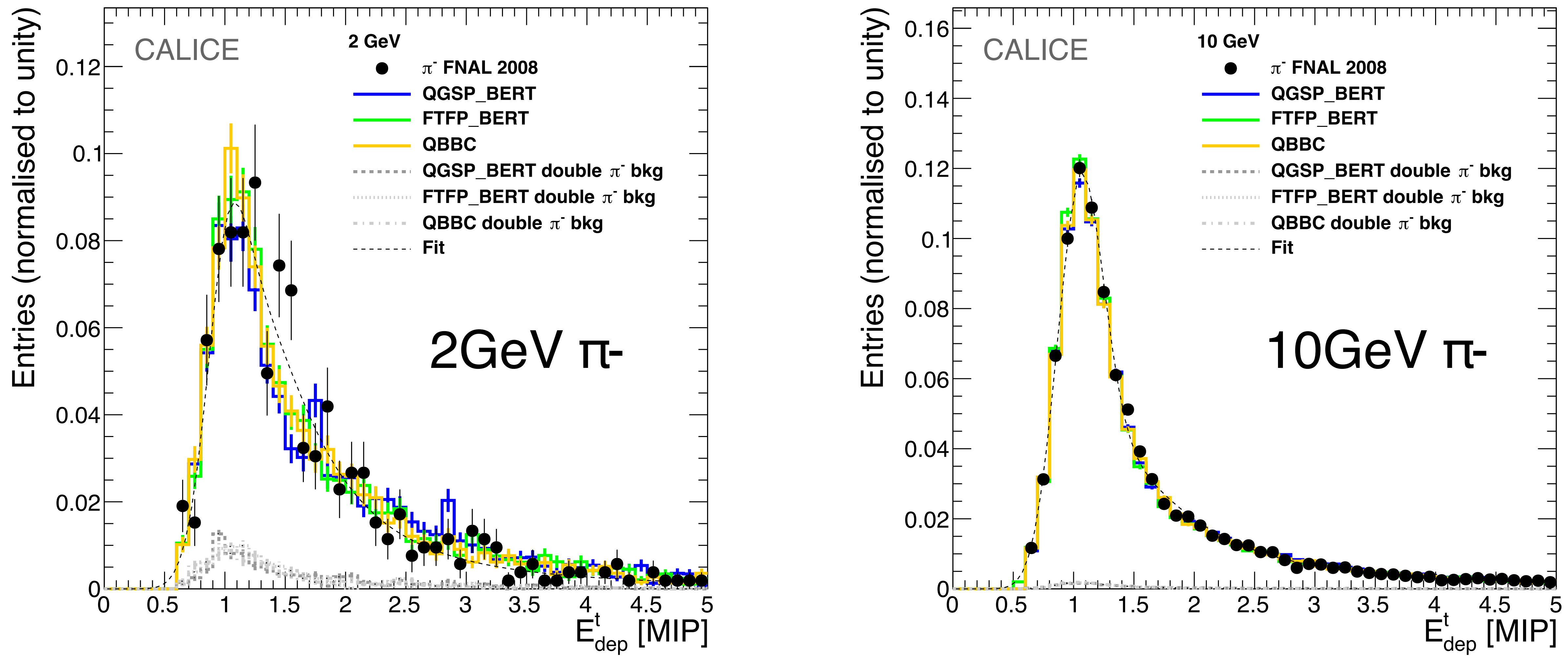
Hadronic Shower Studies

Track Segments@SiW-ECAL, AHCAL

- **Similar studies with track segments with SiW-ECAL and AHCAL**
- **SiW-ECAL**
  - Test beam data: 2-10GeV pions@FNAL
- **AHCAL**
  - Test beam data: 10-80GeV pions@CERN-SPS

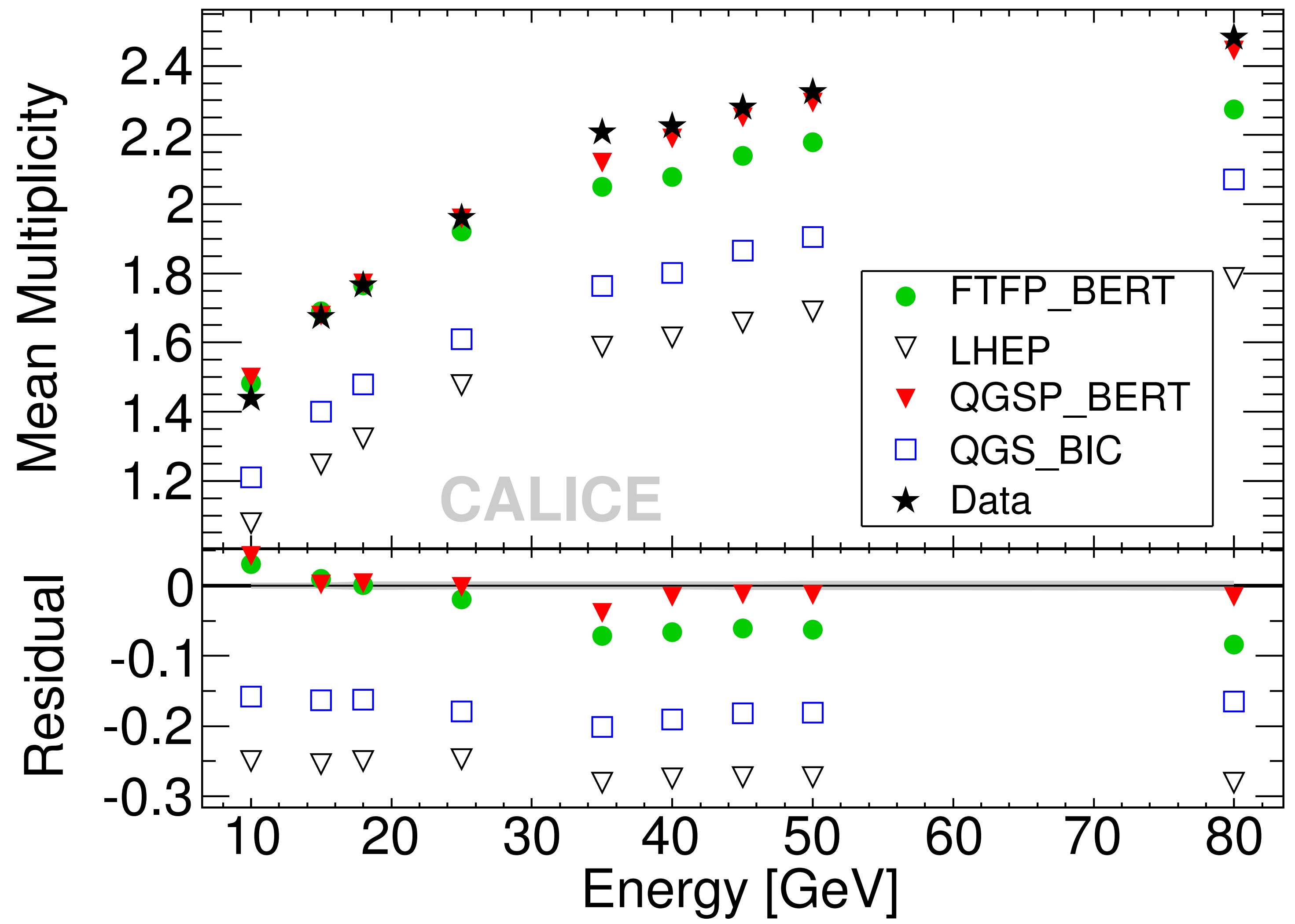


Energy deposition of secondary tracks @SiW-ECAL



NIMA937(2019)41

Mean track multiplicity @AHCAL



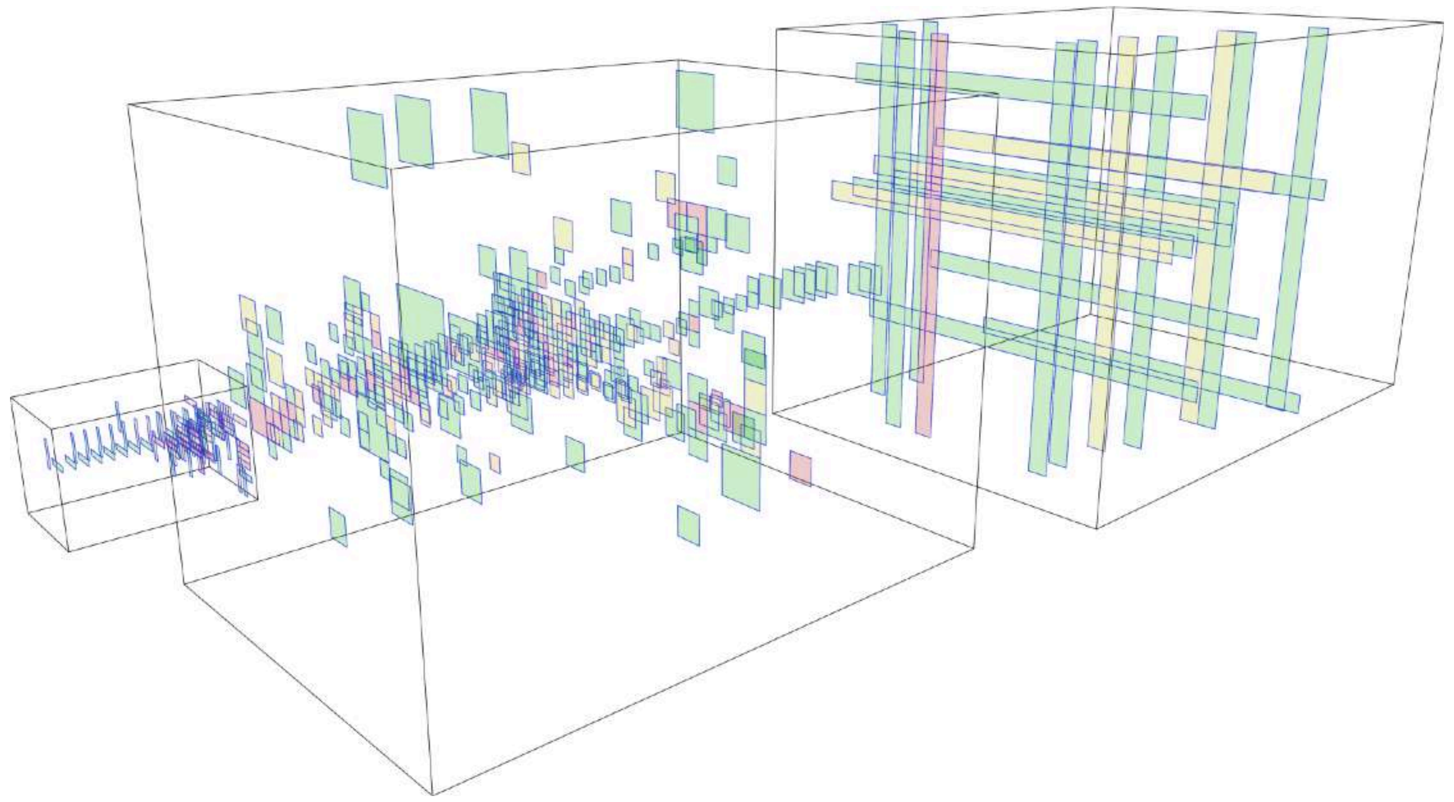
JINST 8(2013)P09001

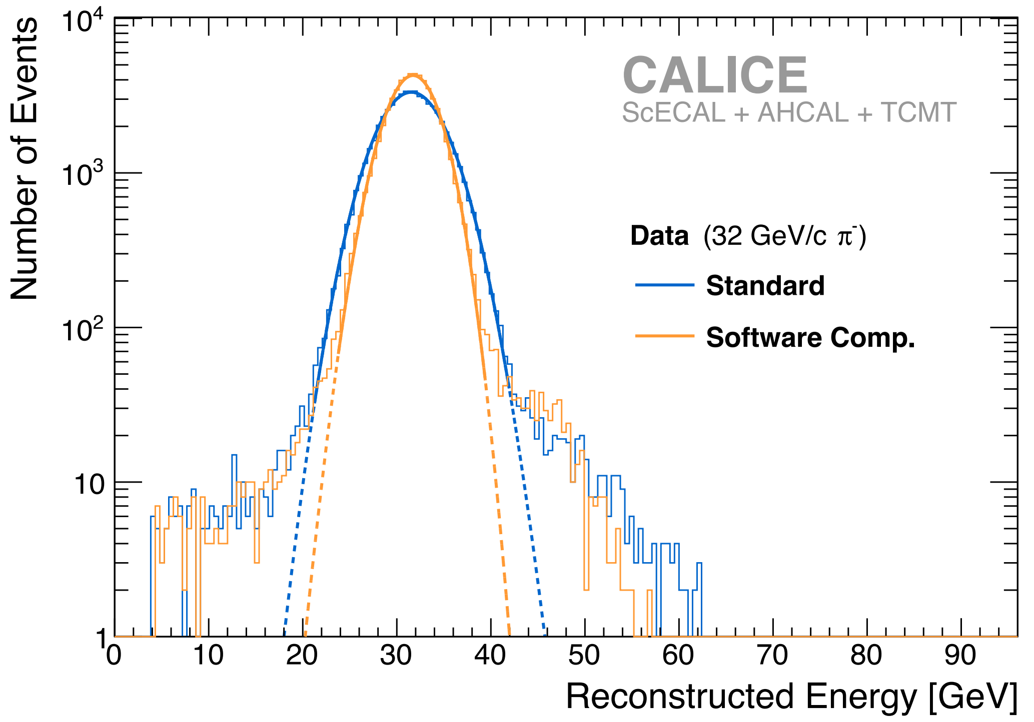
Hadronic Energy Reconstruction

JINST 13(2018)P12022

Software Compensation@Scintillator Calorimeters

- **Energy reconstruction with software-based compensation**
  - Compensate e/h by assigning weight depending on energy density
    - Higher shower density for electromagnetic component
    - Lower shower density for hadronic component
  - Test beam: 4-32GeV pions@FNAL with Sc-ECAL+AHCAL+TMCT

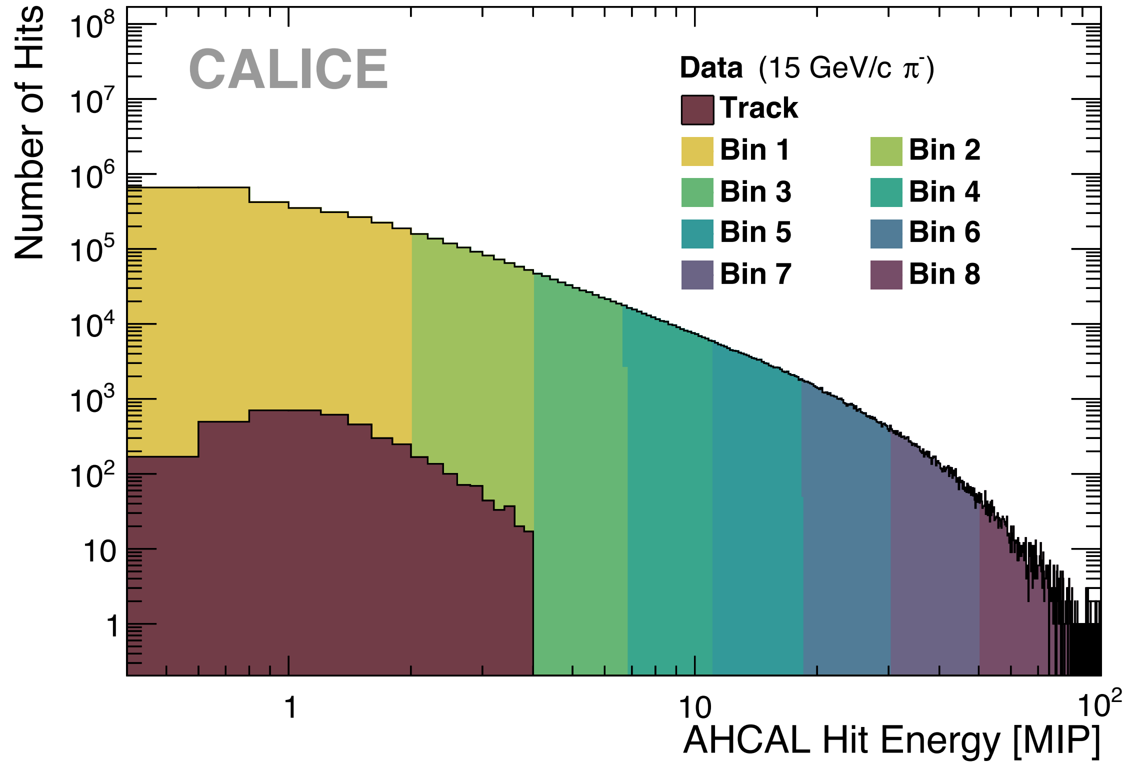




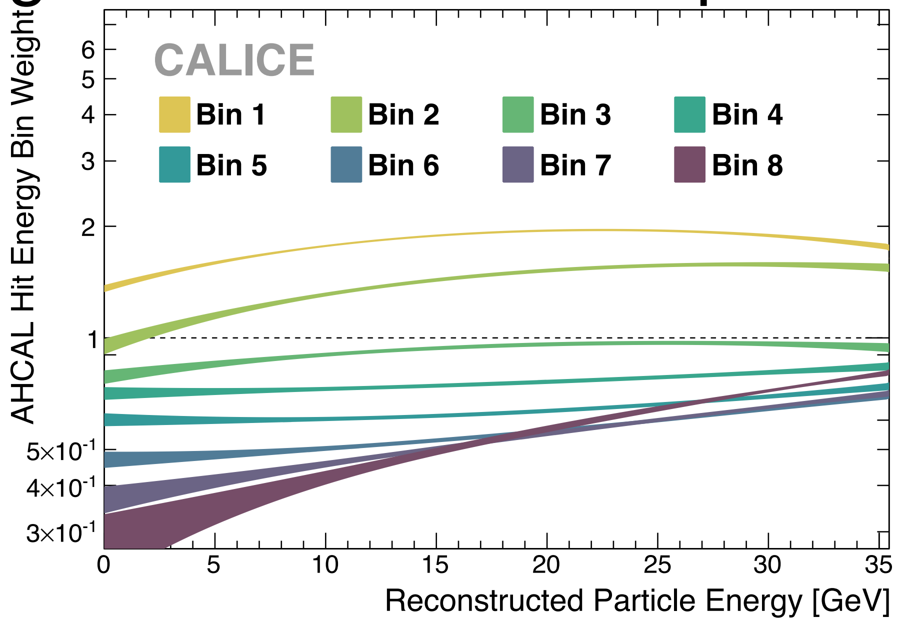
- **Energy resolution significantly improved by 10-20%**

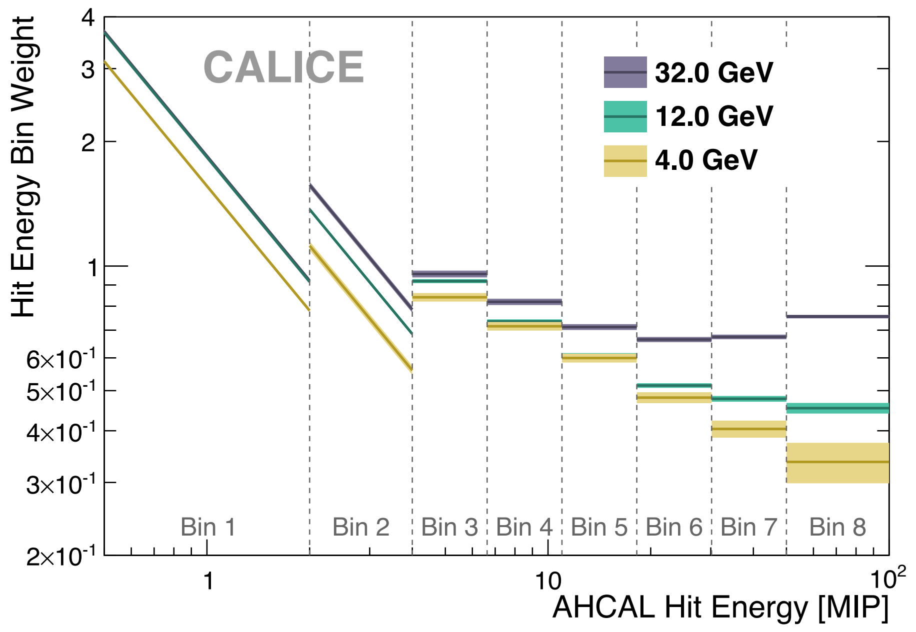
$$E_{\mathrm{rec}}^{\mathrm{SC}} = w_{\mathrm{ECAL}} \cdot \left(\sum_{i}^{\mathrm{bins}} \alpha_i \left(E_{\mathrm{est}}\right) \cdot E_i^{\mathrm{ECAL}} + E_{\mathrm{track}}^{\mathrm{ECAL}} \right)$$
$$+ w_{\mathrm{HCAL}} \cdot \left(\sum_{i}^{\mathrm{bins}} \beta_i \left(E_{\mathrm{est}}\right) \cdot E_i^{\mathrm{HCAL}} + E_{\mathrm{track}}^{\mathrm{HCAL}} + \gamma \left(E_{\mathrm{est}}\right) \cdot E_{\mathrm{sum}}^{\mathrm{TCMT}} \right)$$

Hit energy distribution (15GeV π-)

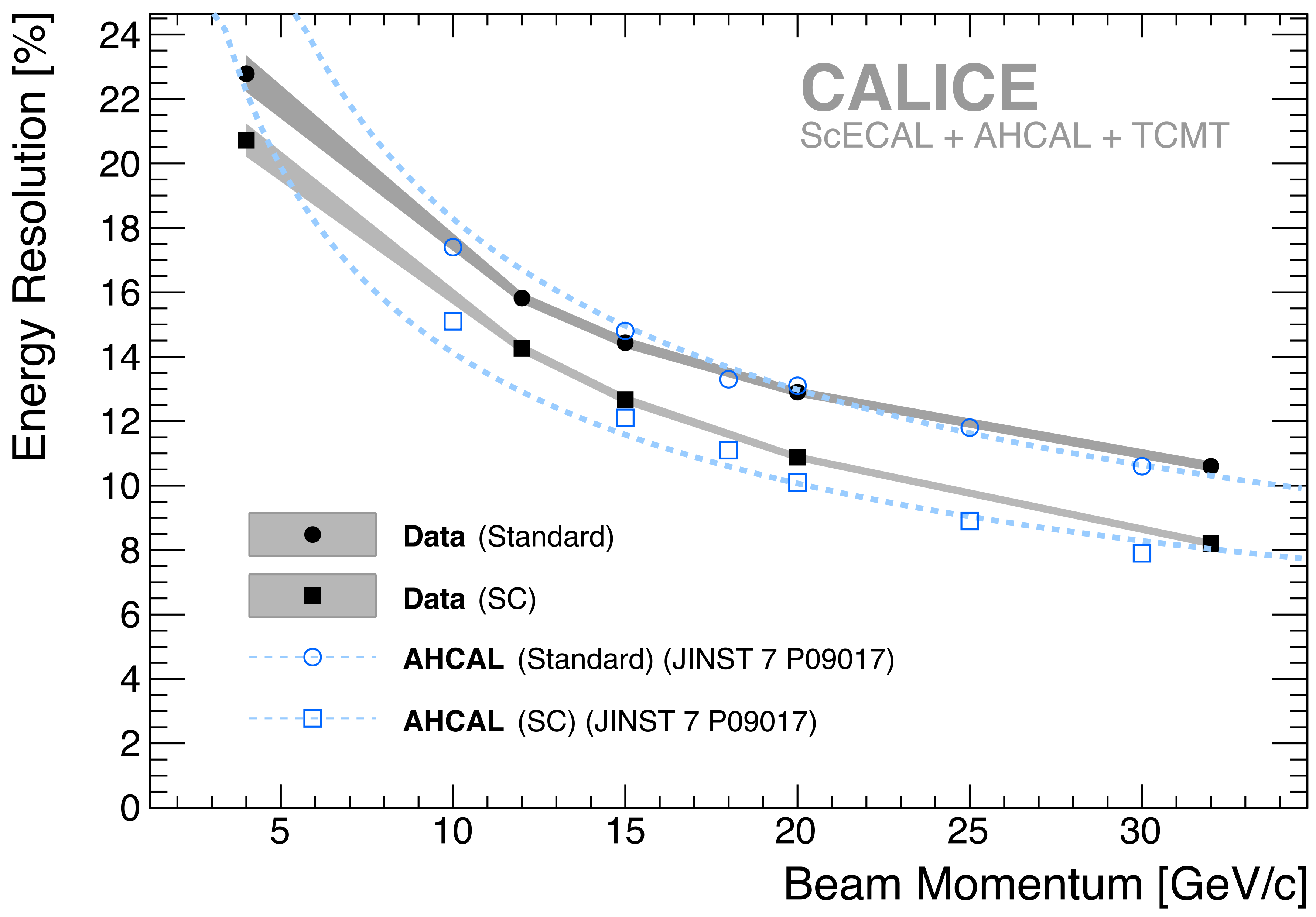


Weights for software compensation





Energy resolution (standard vs. software compensation)



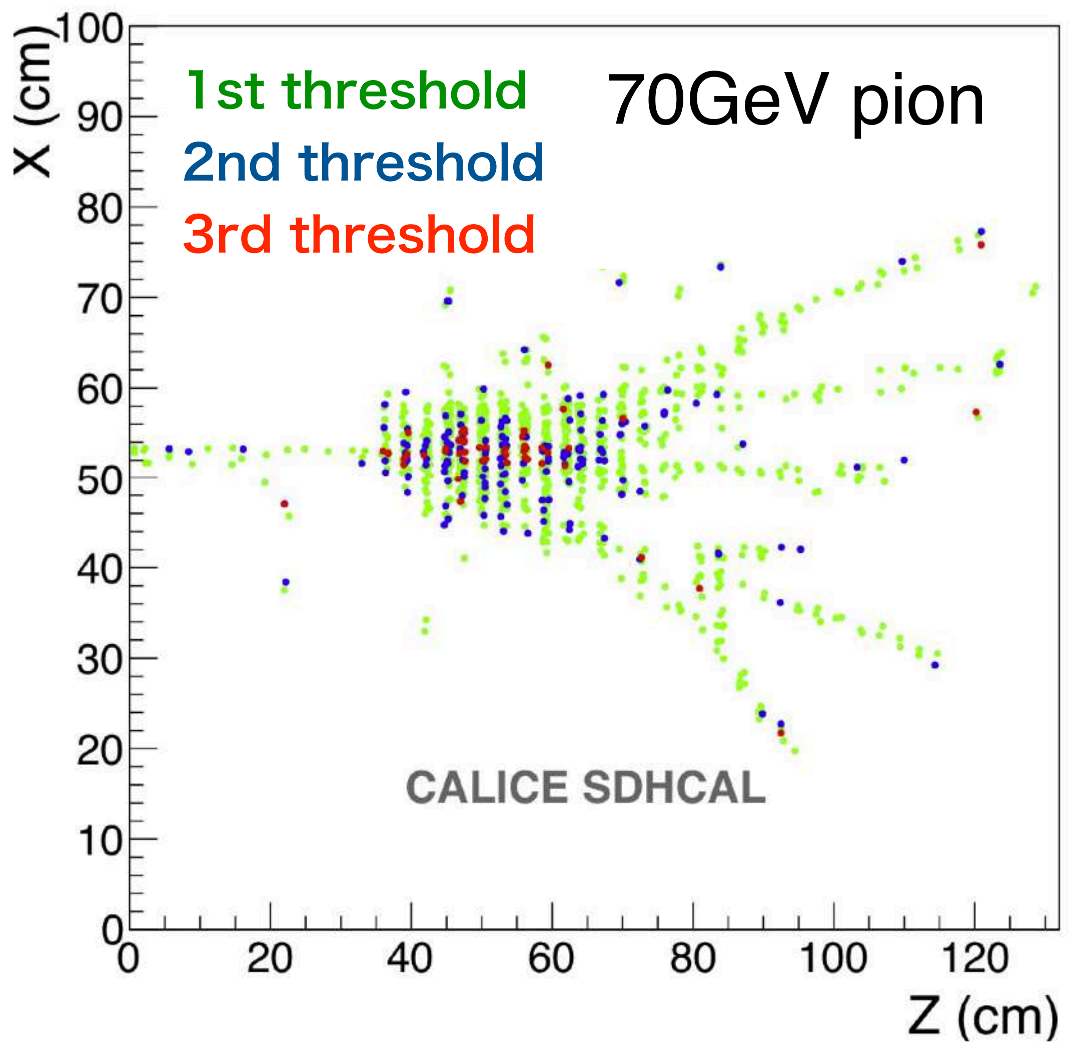
Hadronic Energy Reconstruction

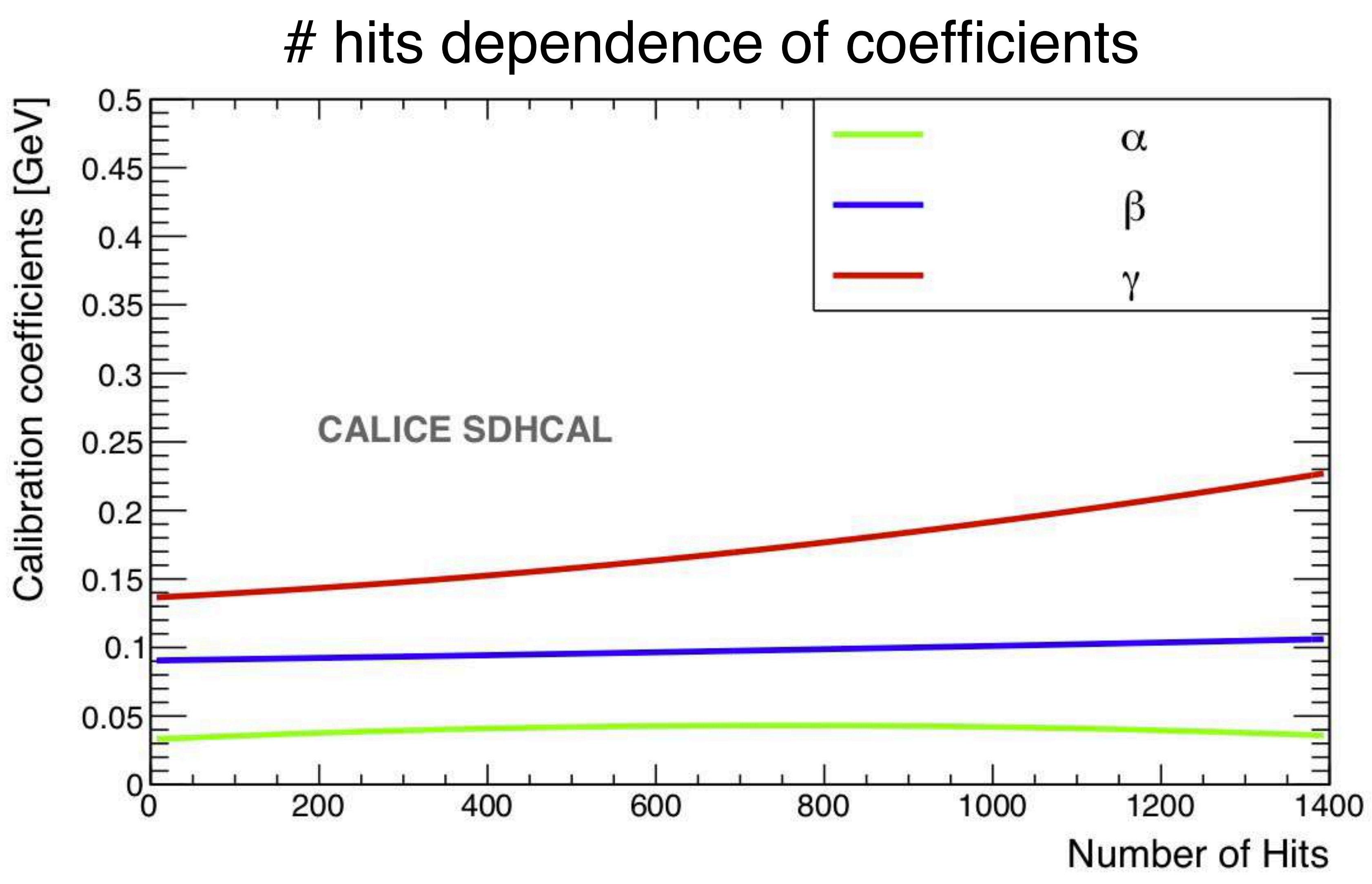
JINST 11(2016)P04001

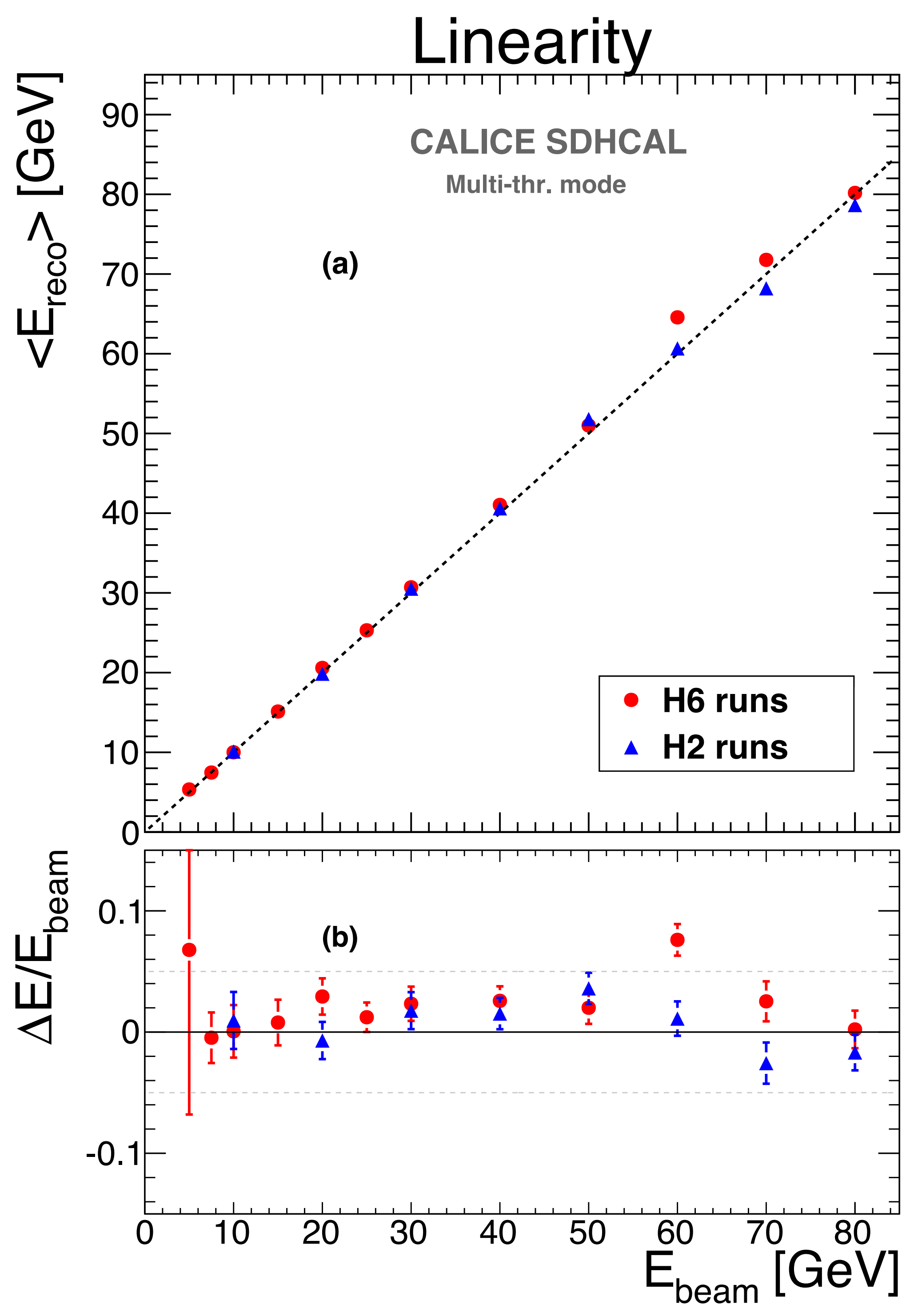
Multi-thresholds Readout@SDHCAL

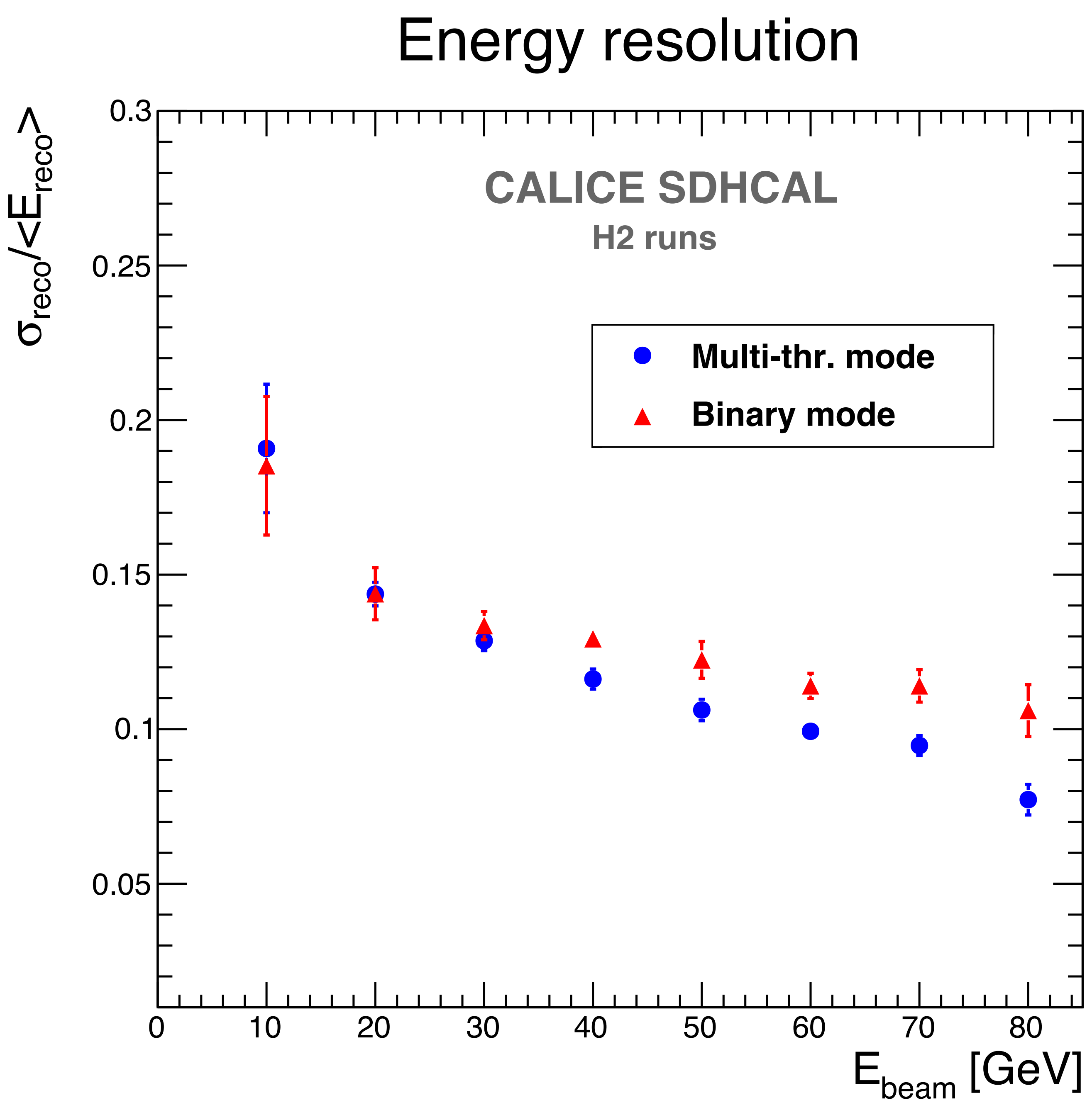
- **Multi-thresholds readout of SDHCAL**
  - SDHCAL version of "software compensation"
  - Different weights depending on three thresholds
    - N_1, N_2, N_3: exclusive number of hits associated to 1st, 2nd, 3rd thresholds
    - α, β, γ: quadratic functions of total number of hits
  - Parameters fit using test beam data @CERN SPS (5, 10, 30, 60, 80GeV)
  - Mitigate saturation of energy resolution at high energy

$$E_{\mathrm{reco}} = \alpha N_1 + \beta N_2 + \gamma N_3$$







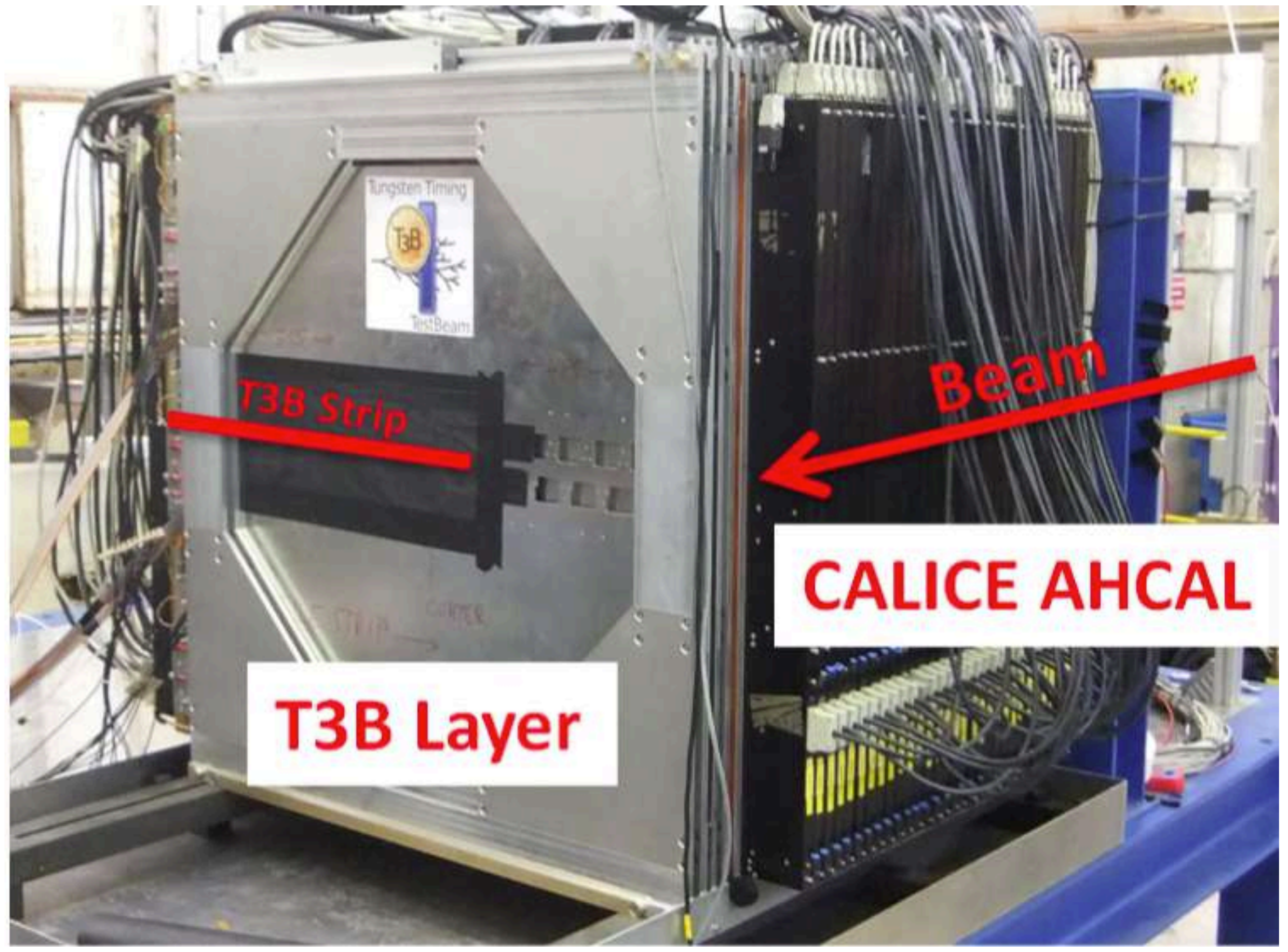


Time Structure of Hadronic Shower

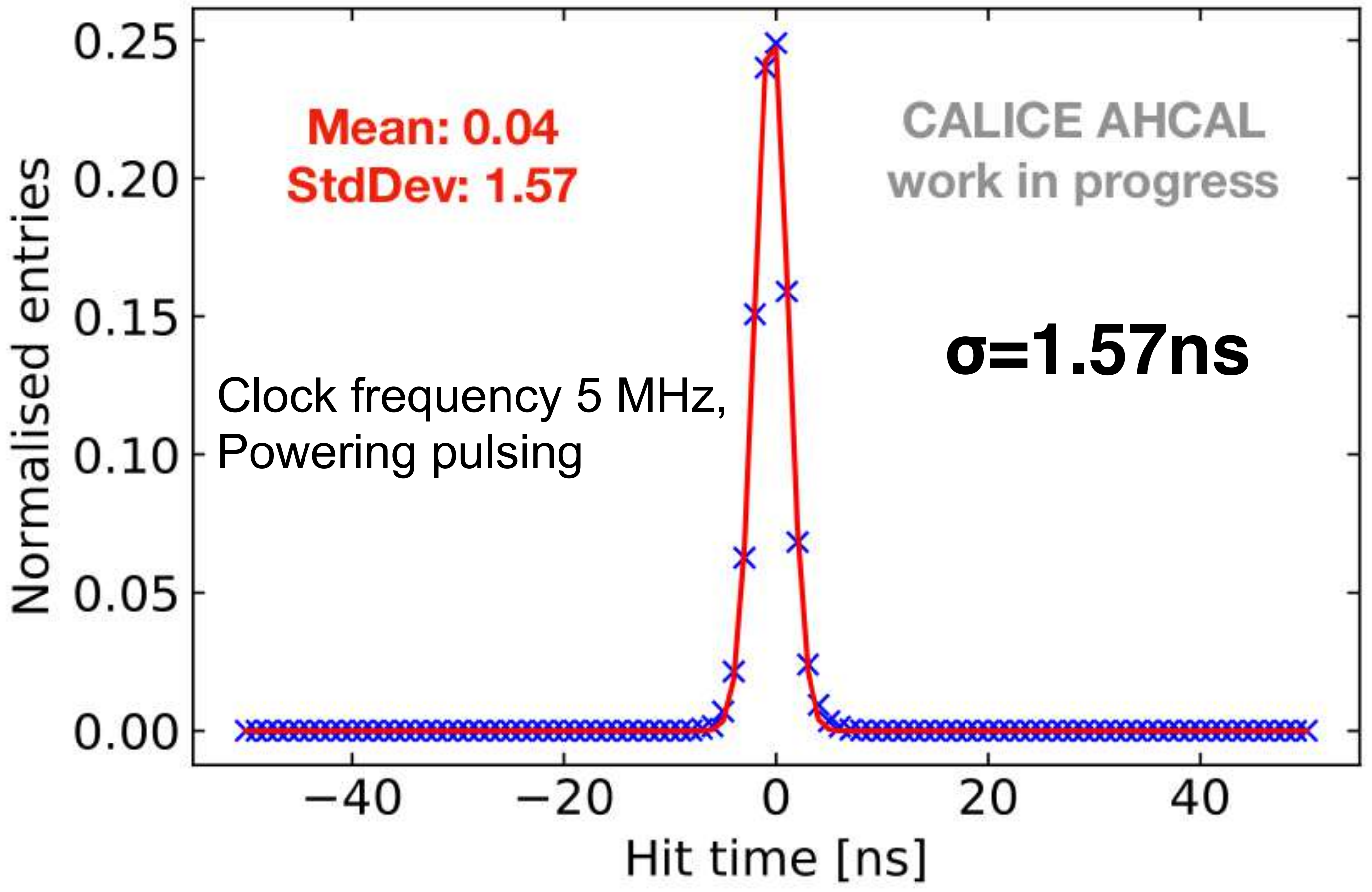
Toward 5D-Calorimetry

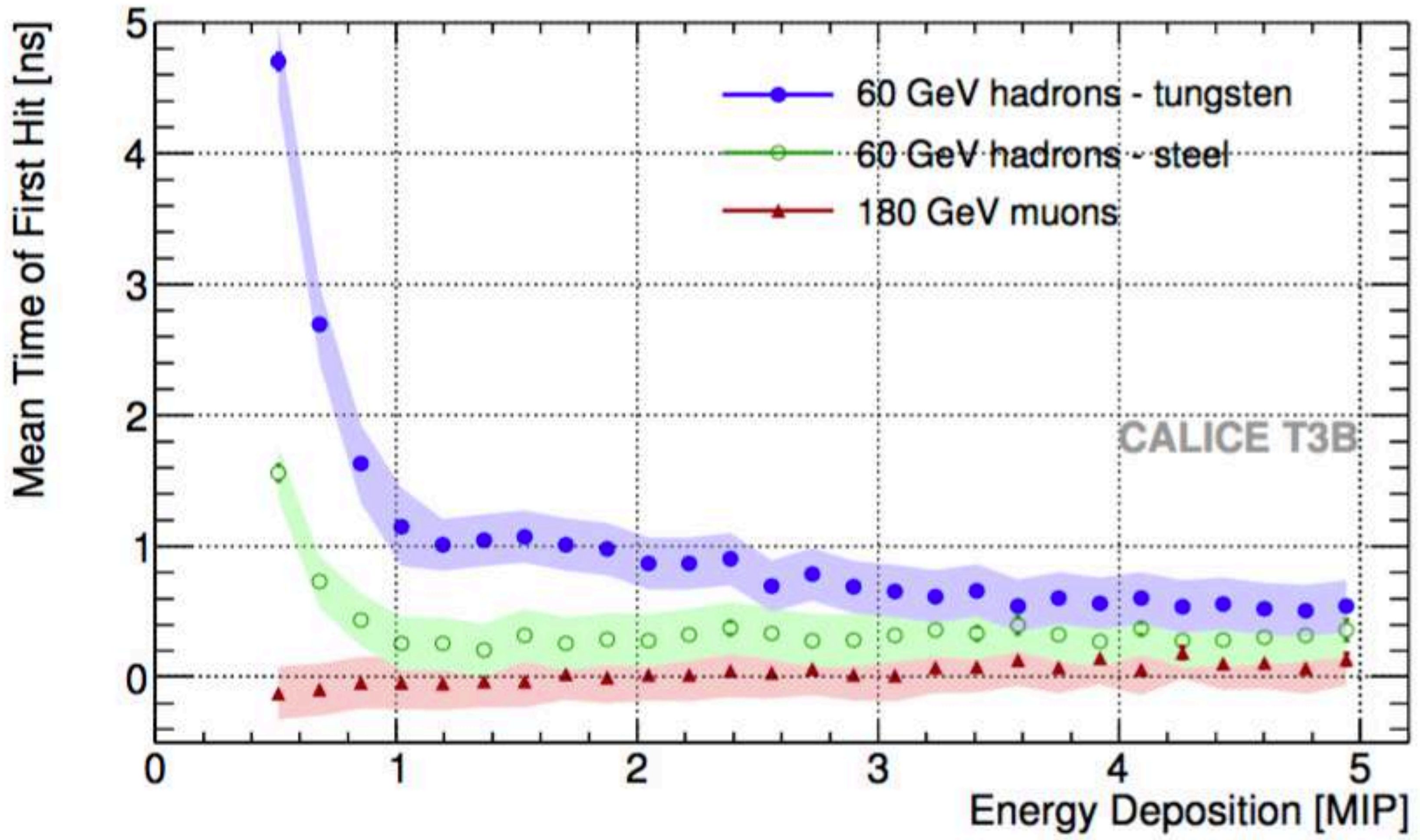
- **CALICE T3B Experiment**
  - Small dedicated setup of 15 scintillator tiles (30×30mm²) with SiPMs placed behind CALICE hadron calorimeters (W-AHCAL, Fe-SDHCAL)
  - Radial sampling of structure of hadronic showers with sub-ns time resolution over 2.4µs time window
  - More late component in tungsten than in steel
- **Hit time measurement capability at AHCAL technological prototype**
  - Hit time resolution of 1.6ns for muons @AHCAL technological prototype
    - Currently limited by front-end electronics
  - Analysis for hadrons also in progress

CALICE T3B JINST 9(2014)P07022



Hit time resolution with AHCAL technological prototype





Summary

- **Development of high-granularity calorimeters for future e^+e^- collider experiments by CALICE collaboration**
    - High granularity calorimeter is a key to the unprecedented jet energy resolution with the particle flow calorimetry
- **Test beam prototypes with high-granularity provide excellent opportunities to study hadronic showers**
    - Detailed studies on spatial and temporal shower structures
    - Optimal energy reconstruction exploiting detailed properties of shower structure
    - Validation of modelling of hadronic shower in GEANT4
- **More results soon to come from recent test beam experiments with technological prototypes**

Backup

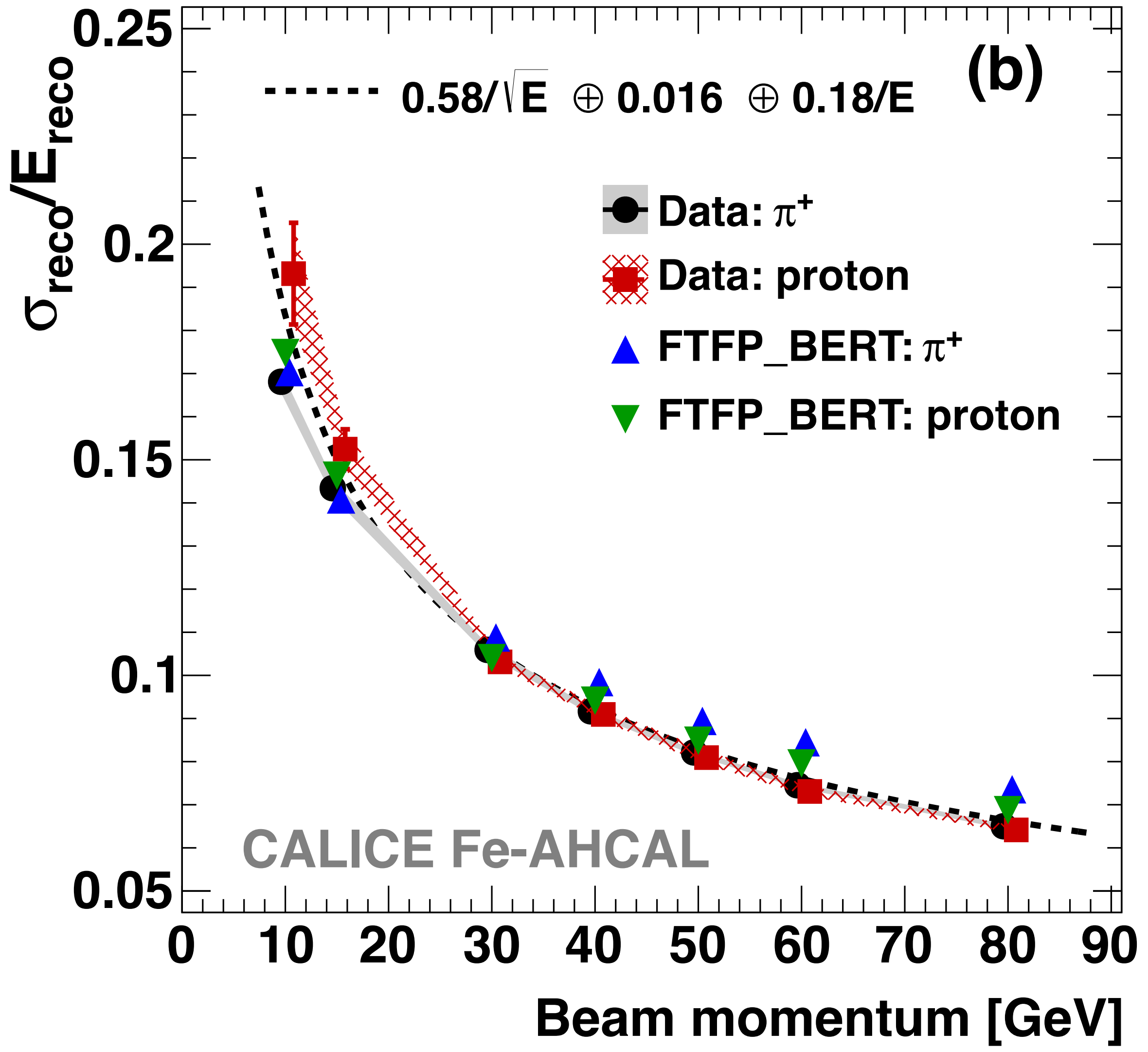
Hadronic Shower Studies

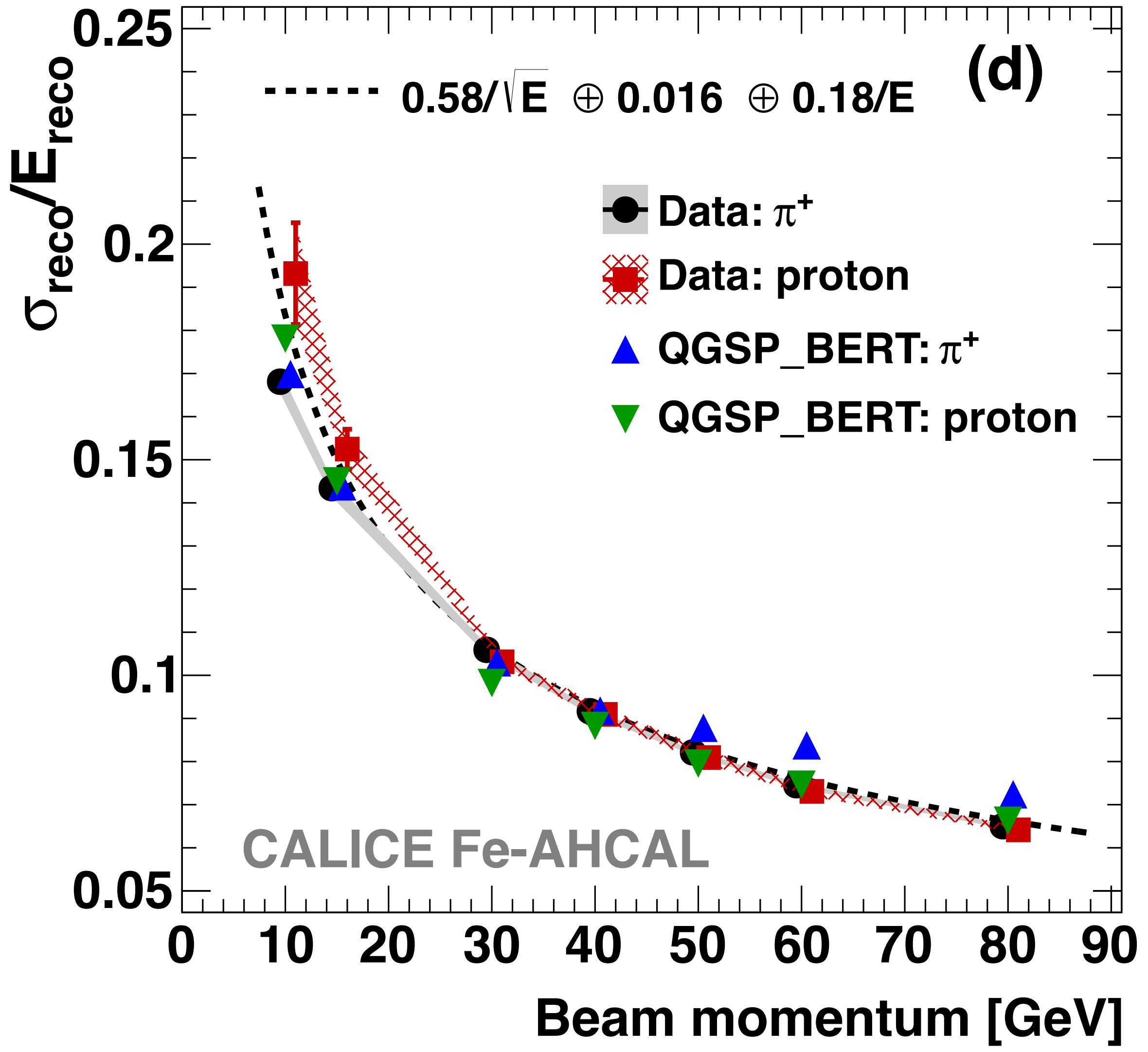
AHCAL

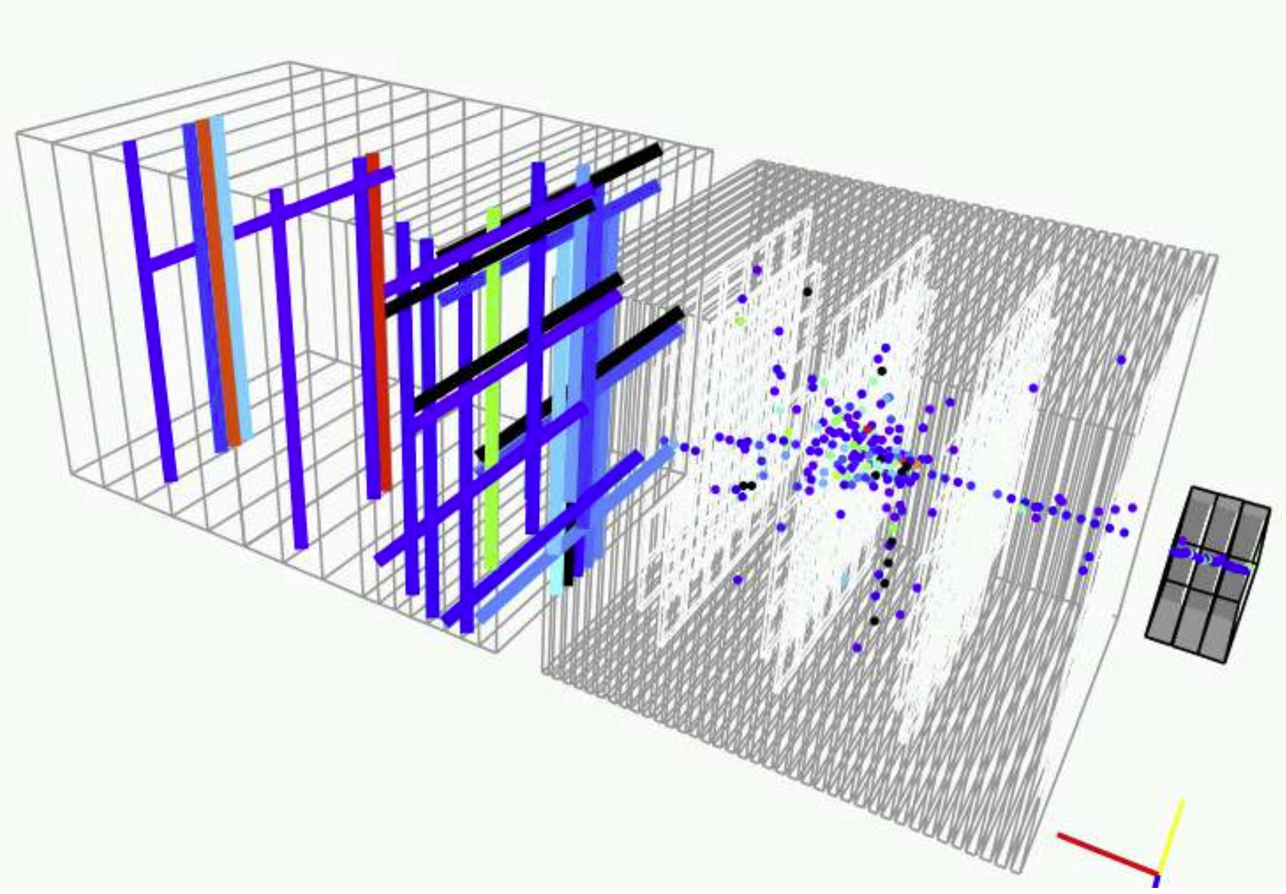
JINST 10 (2015) P04014

- **Hadronic shower studies by AHCAL**
  - Test beam data: positive pion and proton 10-80GeV@CERN and FNAL
  - Simulation
    - GEANT4 ver9.6
    - Physics lists: FTP_BERT, QGP_BERT
- **Comparison between pion- and proton-induced hadronic showers**
  - Longitudinal segmentation allows to measure shower start on event-by-event basis
  - Interaction length extracted from distribution of shower start which can be measured on event-by-event basis
  - Good agreement as calculated from detector compounds

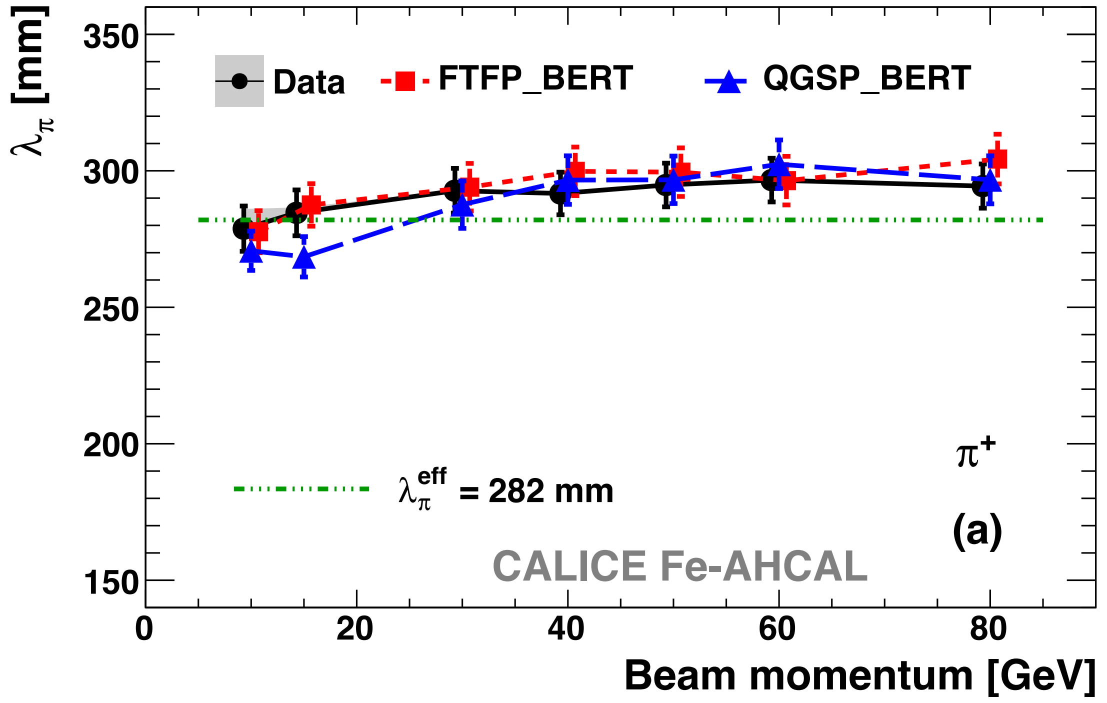
Energy resolution (data vs. MC)

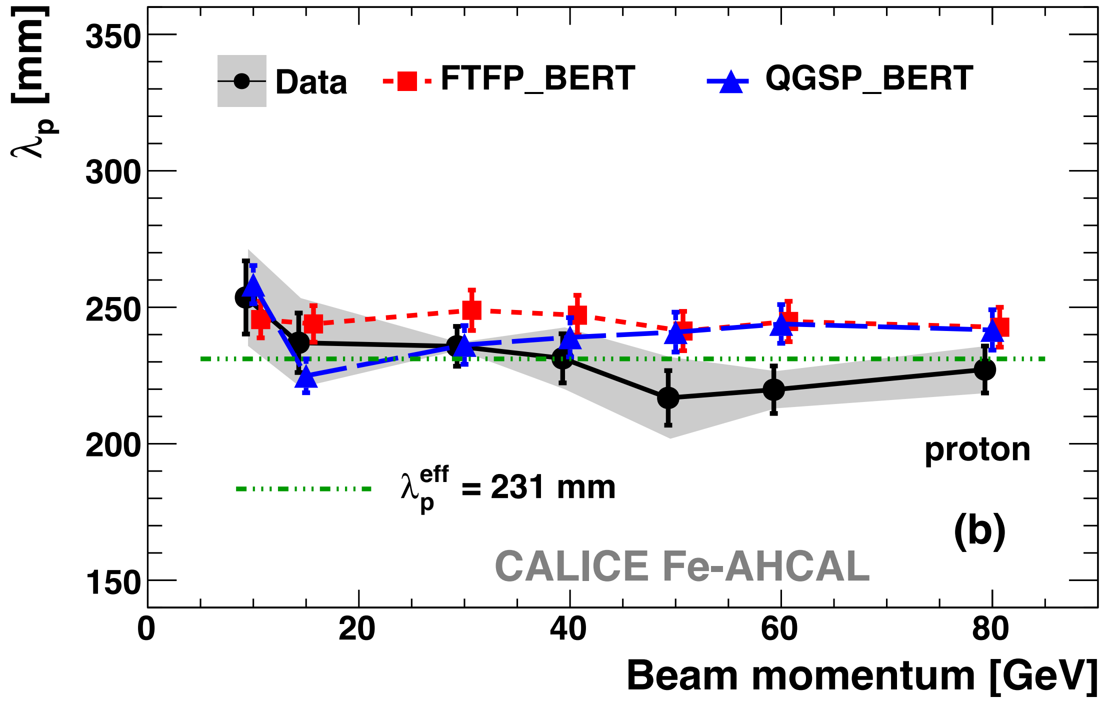






Nuclear interaction lengths for π+ and p



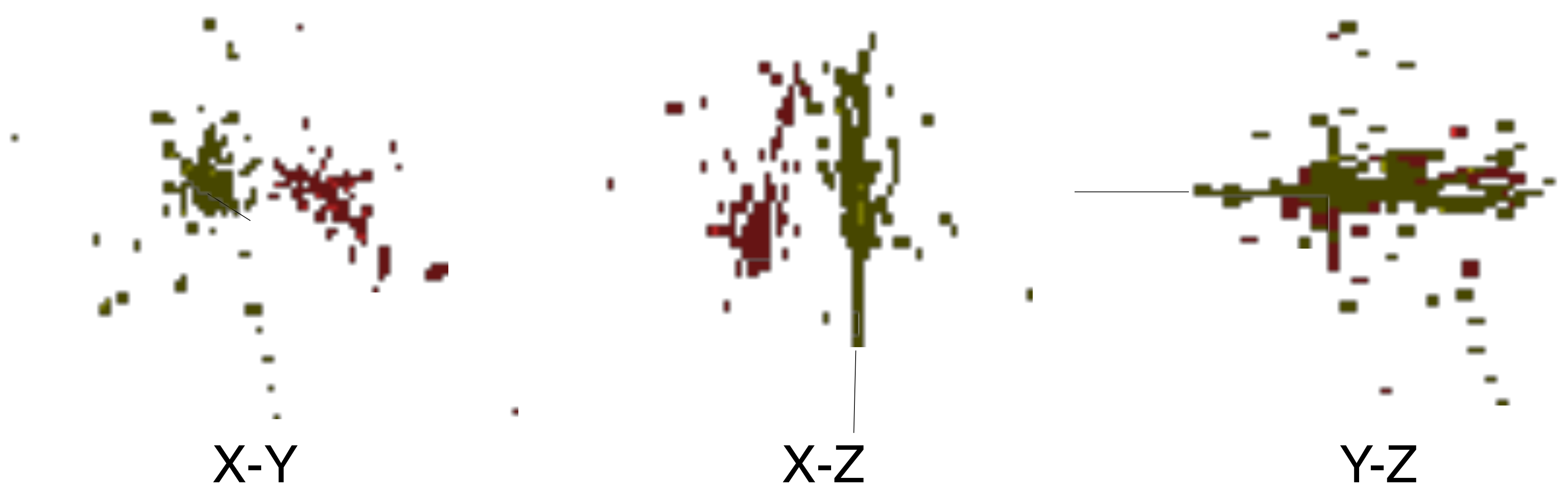


Particle Separation/Identification

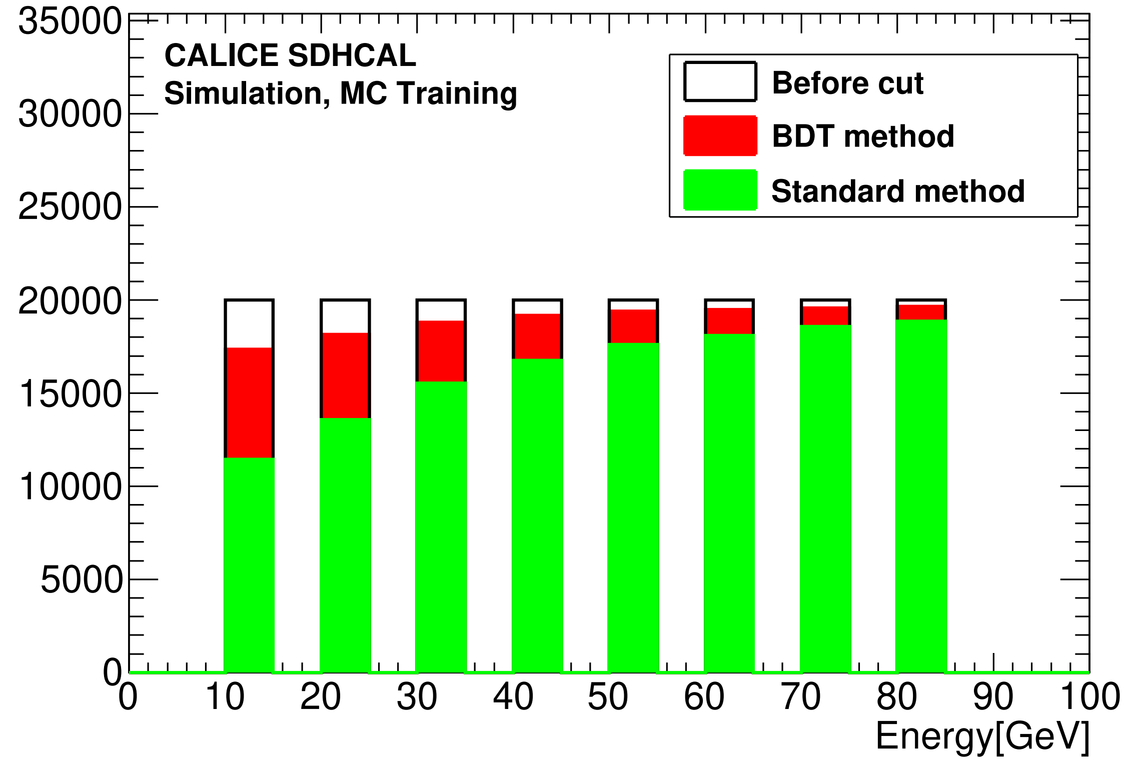
SDHCAL

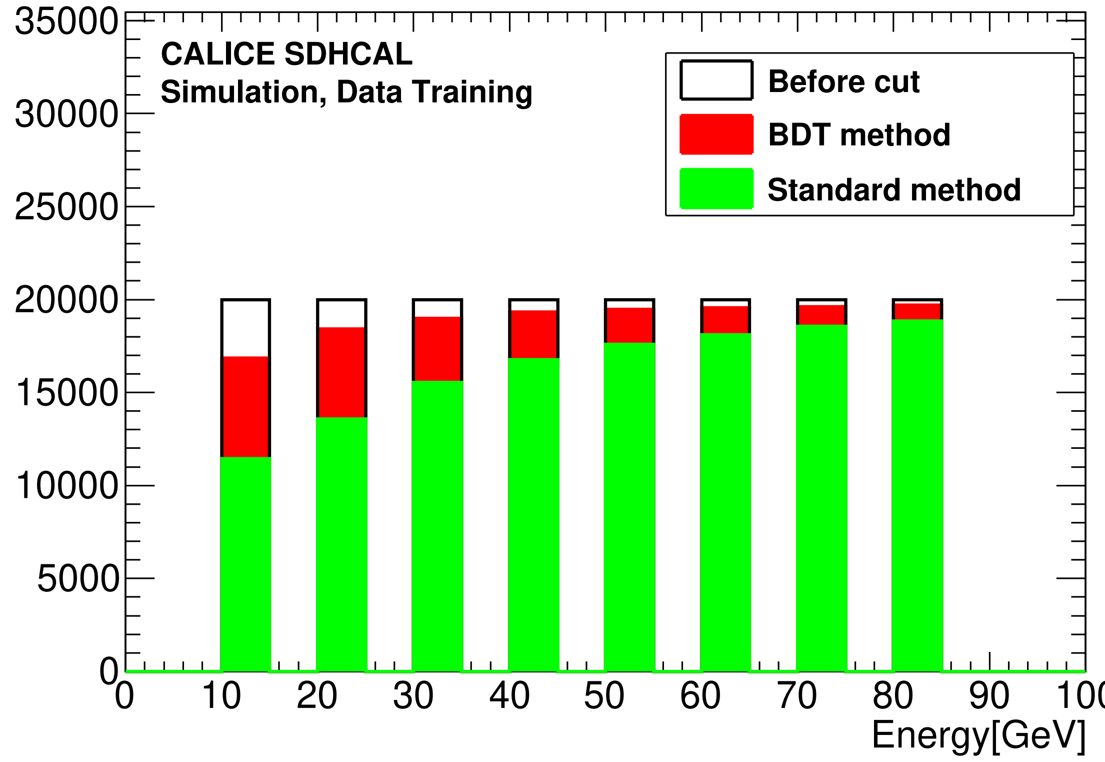
- **Separation of neutral hadron shower from nearby charged hadron shower**
  - Test beam data: 10-80GeV pions @CERN SPS
  - 10GeV “fake” neutral hadron shower is generated by removing initial track segment and overlaid on charged hadron showers
  - **>90% efficiency and purity for nearby showers for distance>15cm**

10GeV neutral hadron overlaid with 30GeV charged hadron



- **Particle identification with multi-variate analysis**
  - Test beam data: 10-80GeV pions @CERN SPS
  - **BDT improves pion selection efficiency at low energies**





arXiv:2004.02972, accepted by JINST

Separation of 10GeV neutral hadron from charged hadron