Validation of Geant4 hadronic models using AHCAL test beam data

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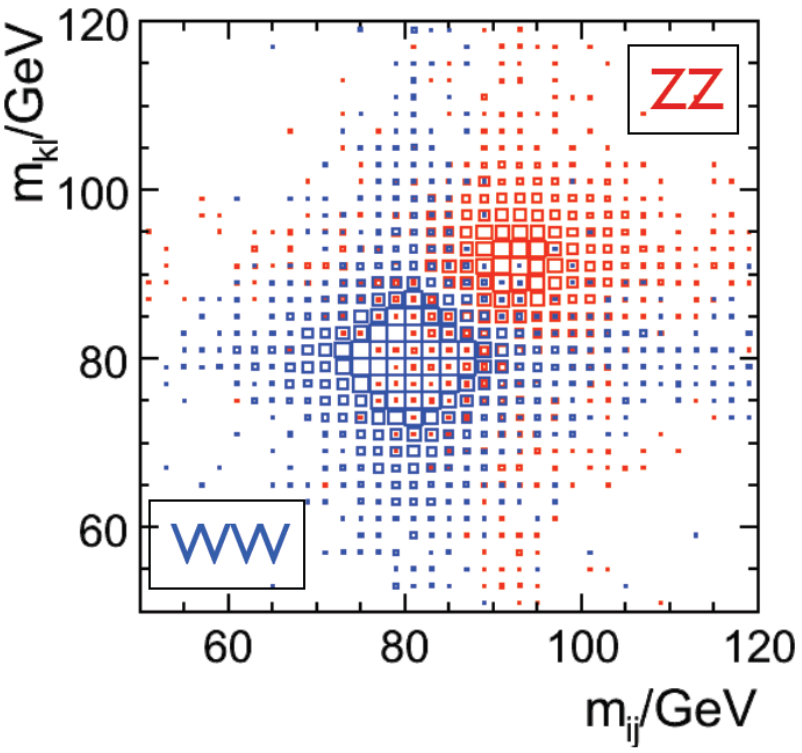
- Hadron showers and calorimeters
- Validation of hadronic shower models
  - Shower shapes and sub-structure
  - Energy resolution, compensation
  - Particle flow with test beam data
- Summary

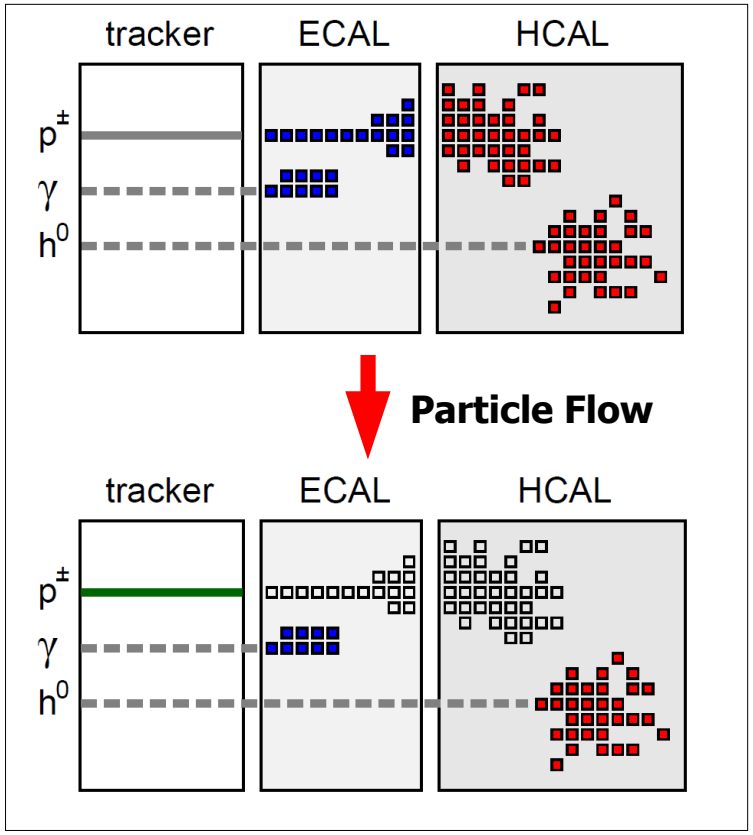
Jet physics at a Linear Collider

Physics goal: Separation of hadronic W, Z decays

→ Jet energy resolution: ΔE/E = 30%/sqrt(E)

→ Particle Flow: Detect each particle in a jet, high granularity required





Calorimeter requirements

- **Very high granularity** required for Particle Flow
  - → ECAL: Cell size < Moliere radius, longitudinally < $1X_0$
  - → HCAL: Cell size ~ Moliere radius, longitudinally ~ $1X_0$
- Explosion of channel count
  - → ECAL: ~ 100 M
  - → HCAL: ~ 10 M

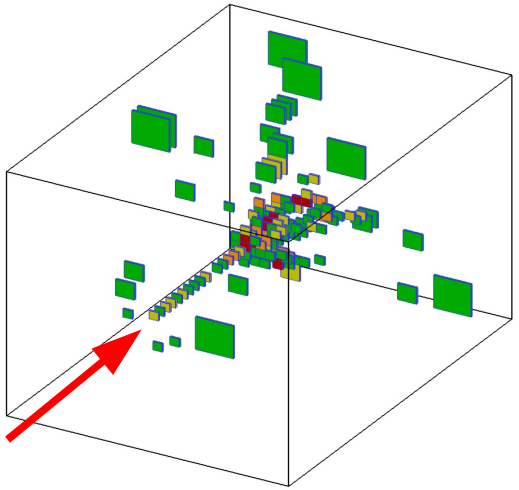
Factor of 1000 more than typical LHC calorimeters!

- **Questions:**
  - Can such detectors be built?
  - What is their performance?
  - Which reconstruction techniques are possible?
  - Can such detectors be calibrated and operated in stable mode?
  - What are the relative merits of different read out techniques?
  - Can we trust the simulations?
    - → **Extensive test beam programs needed!**

CALICE: imaging calorimeters

Intermediate task: Understand test beam data and validate Geant4 models

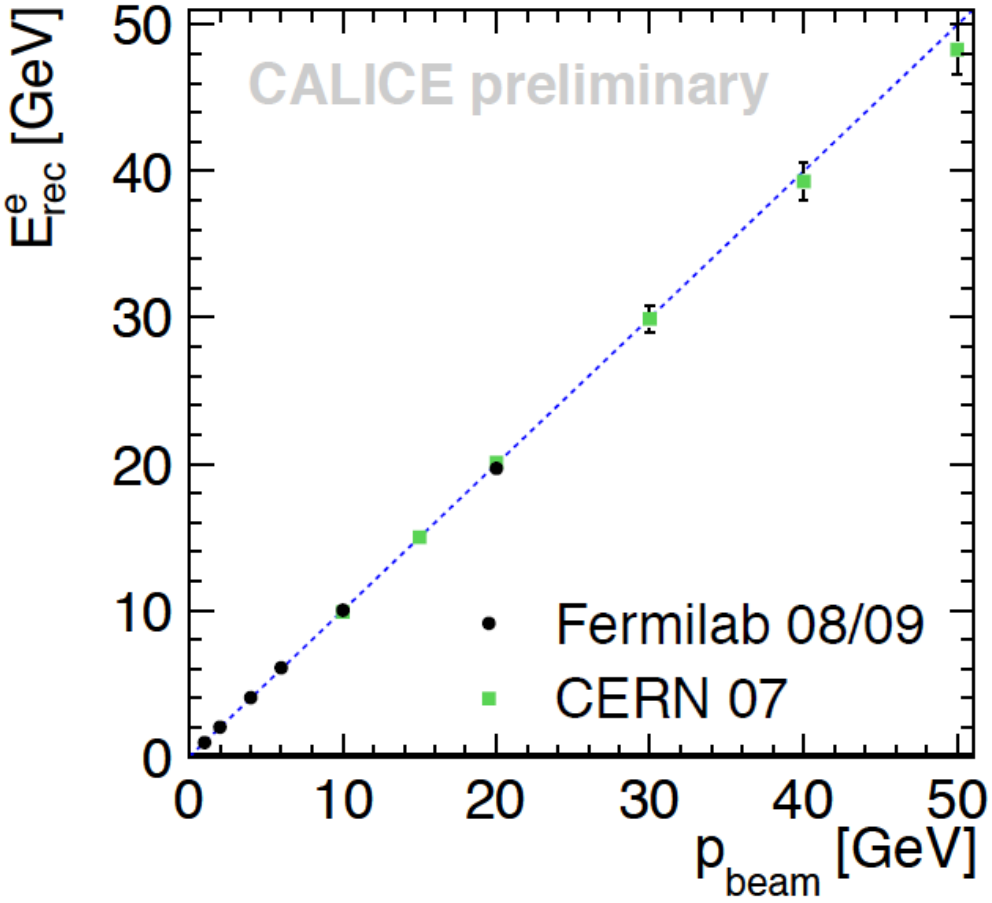
(See Julians talk for latest test beam activities and 2nd generation prototypes)



Focus in Germany:

Analog hadron calorimeter, 3x3x0.3cm³ scintillator tiles read out by silicon photomultipliers

Validation with electron data



- **Linear response**

  (3% non-linearity > 30 GeV)

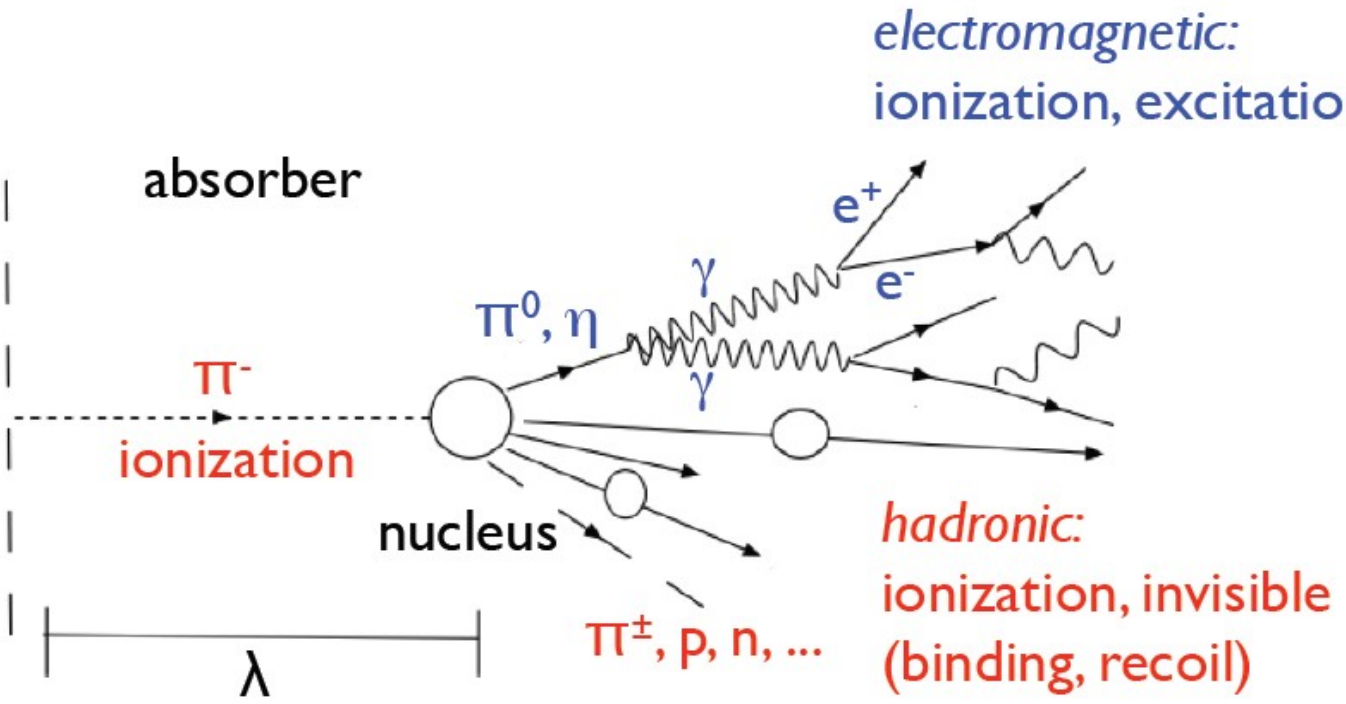
- **Electromagnetic scale**
  - Fermilab

    (41.7 ± 0.3) MIP / GeV
  - CERN

    (42.3 ± 0.4) MIP / GeV
  - Digitized Monte Carlo

    (42.0 ± 0.4) MIP / GeV

Hadronic showers

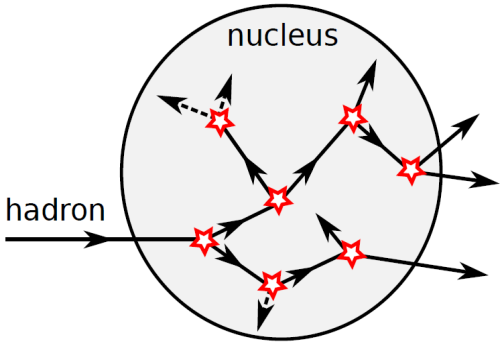


Hadronic showers are difficult to describe due to fluctuating electromagnetic fraction and invisible energy depositions!

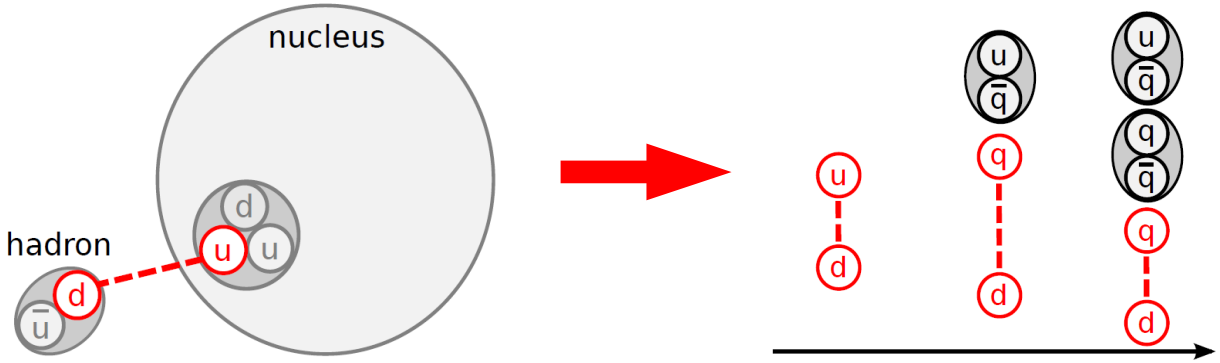
Simulation of hadronic showers

- **Geant4**: Software toolkit for simulating particle interactions with matter
- Different models for inelastic hadron scattering on atomic nuclei

  → **Cascade models**: quark substructure can be neglected



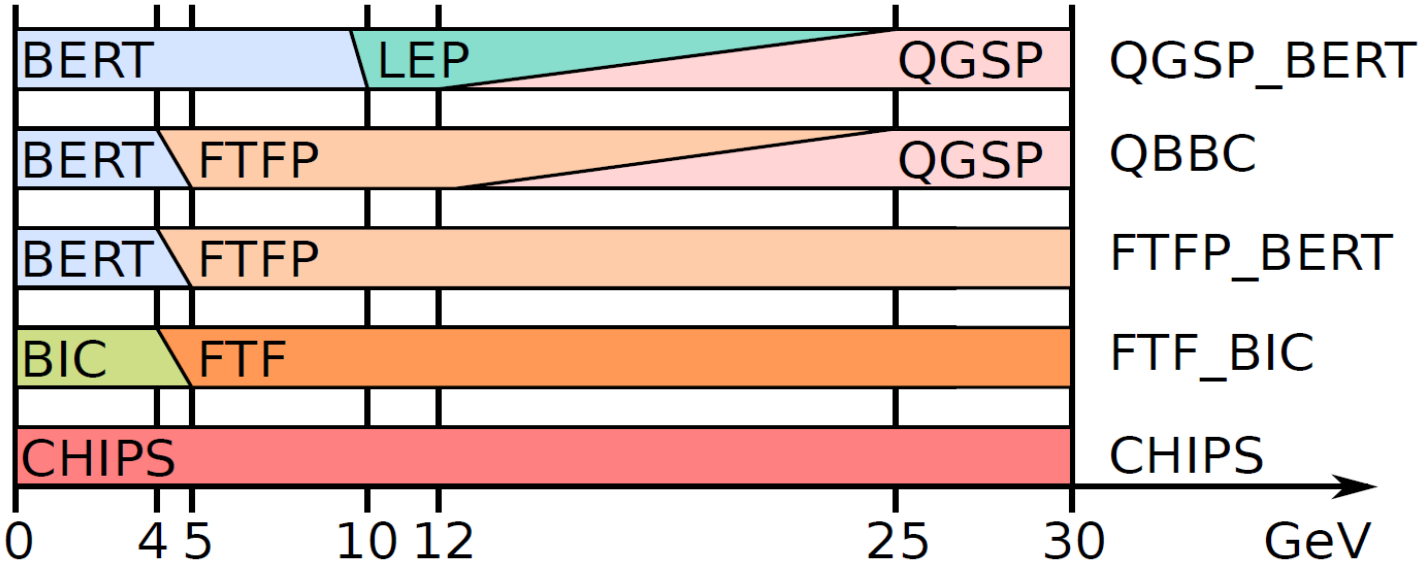
  → **Parton String models**: energies above 5 GeV, quarks become relevant



MC simulations

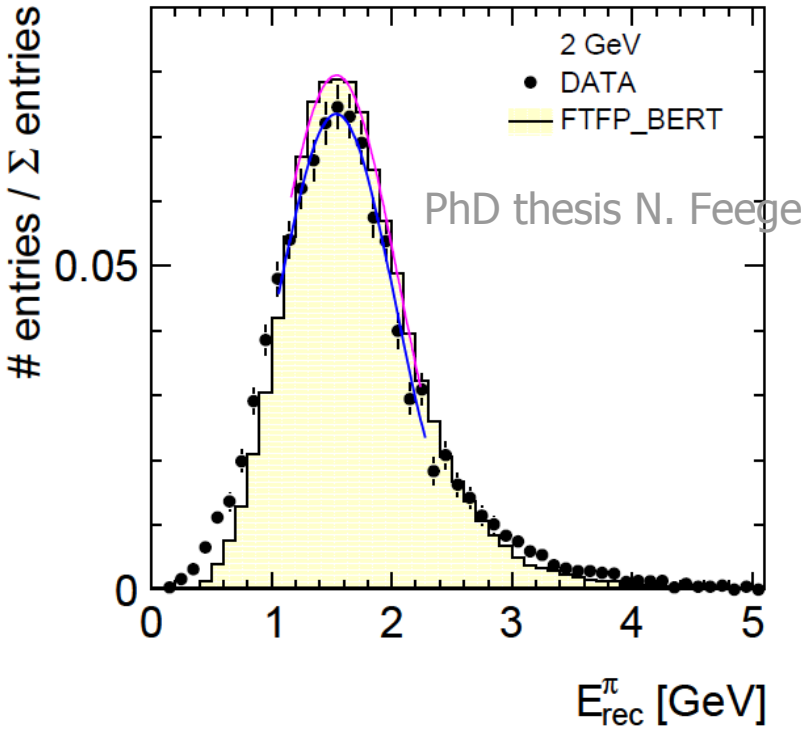
- **Mokka:** Geant4 application able to simulate full ILD detector and TB setup
- Geant4 simulation organized in physics lists combining several models valid at different energies

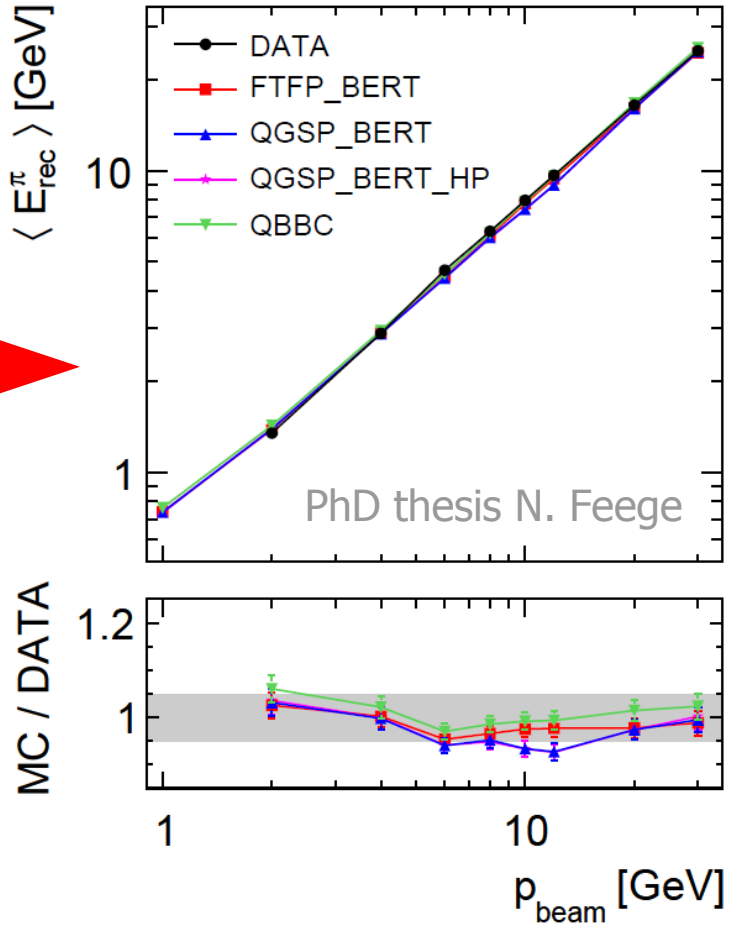
  → Unphysical steps between model validity ranges
- Develop physics lists without LHEP as stop gap
- Develop models for full energy range (CHIPS)



Reconstructed energy

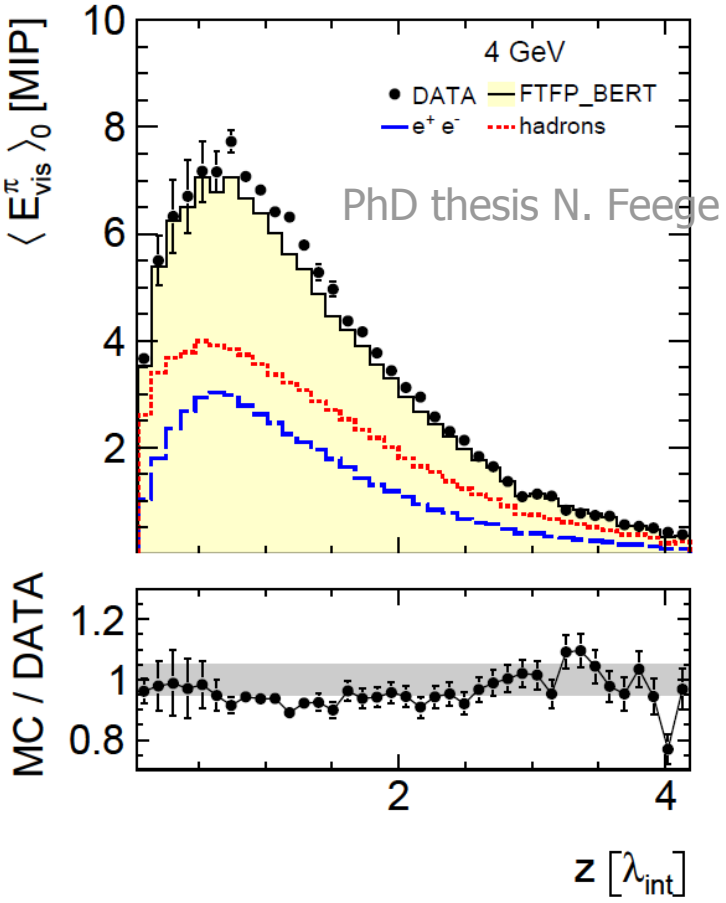
- Compare **reconstructed energy** in data with MC predictions
- FTFP_BERT list works best

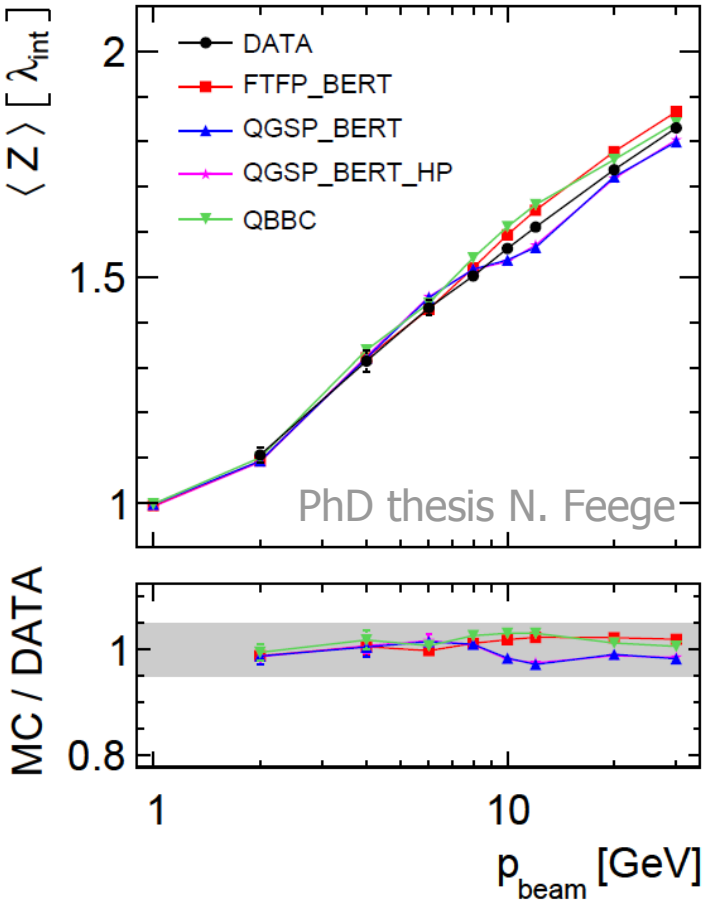




Longitudinal shower shape

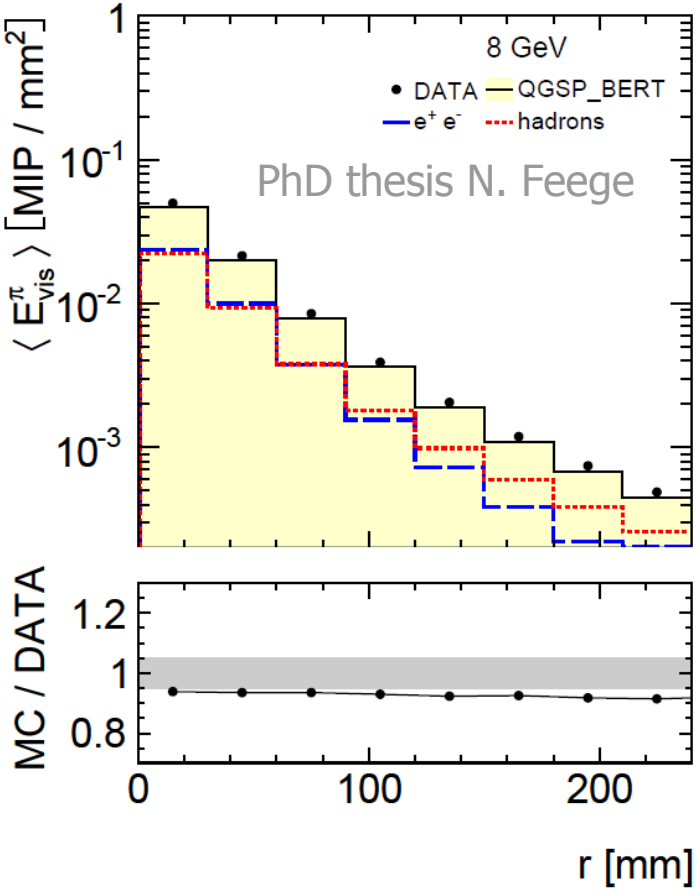
- High granularity allows to measure **shower shapes** in detail
- Measurement sensitive to electromagnetic fraction of cascades

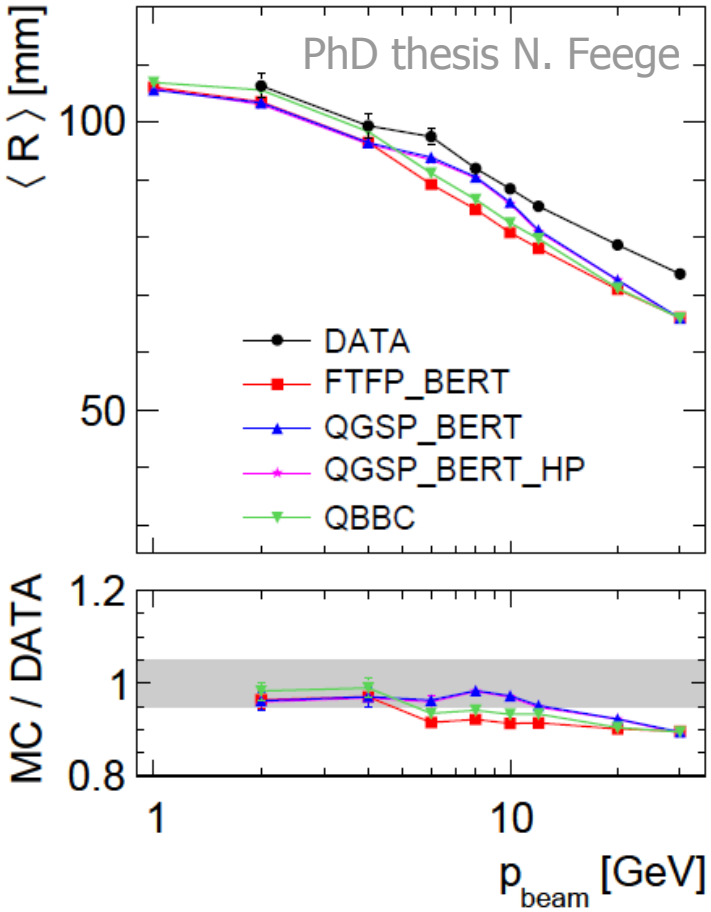




Radial shower profile

- High granularity allows to measure **shower shapes** in detail
- Measurement sensitive to electromagnetic fraction of cascades

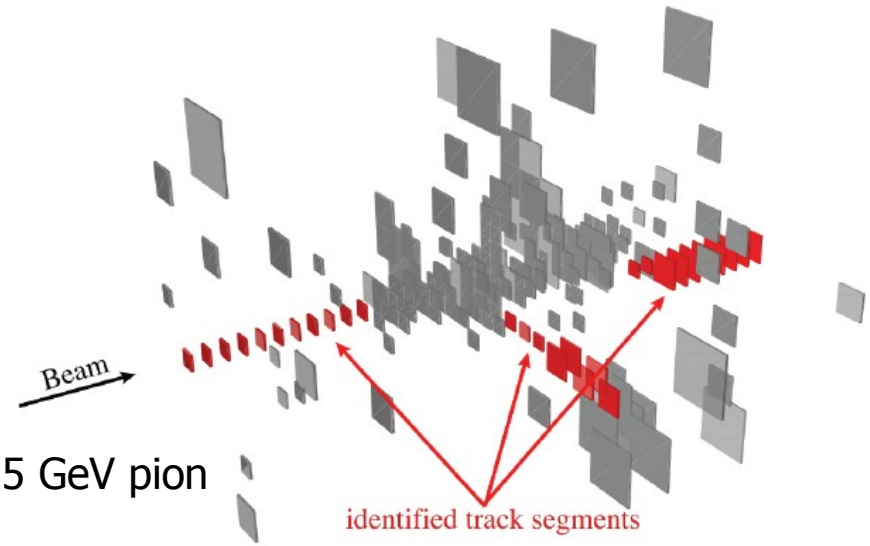




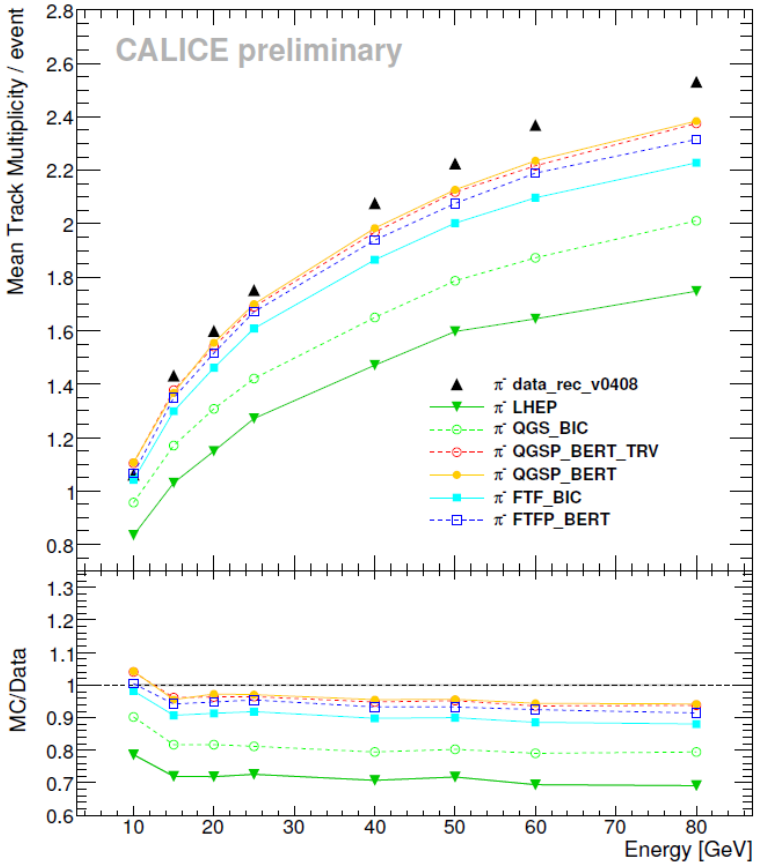
Track segments

- High granularity also allows measurements of shower sub-structures
- Here: **number of track segments**

→ Underestimated by all MC models!

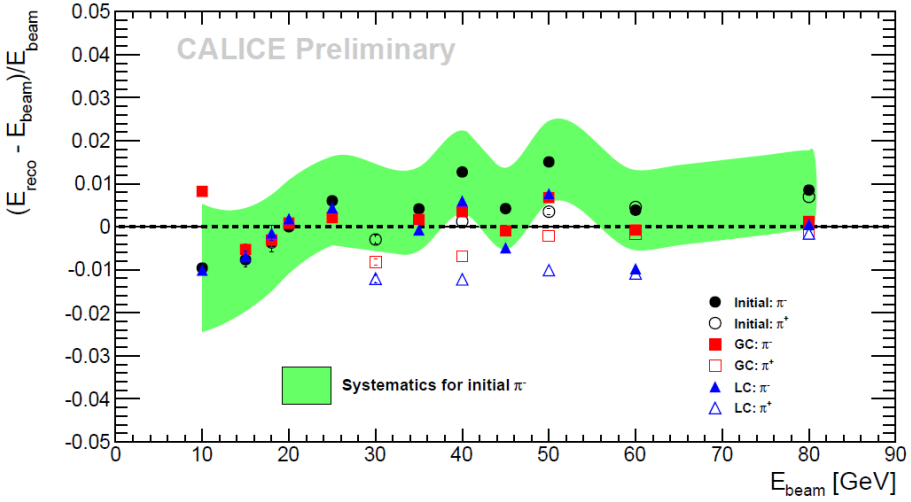


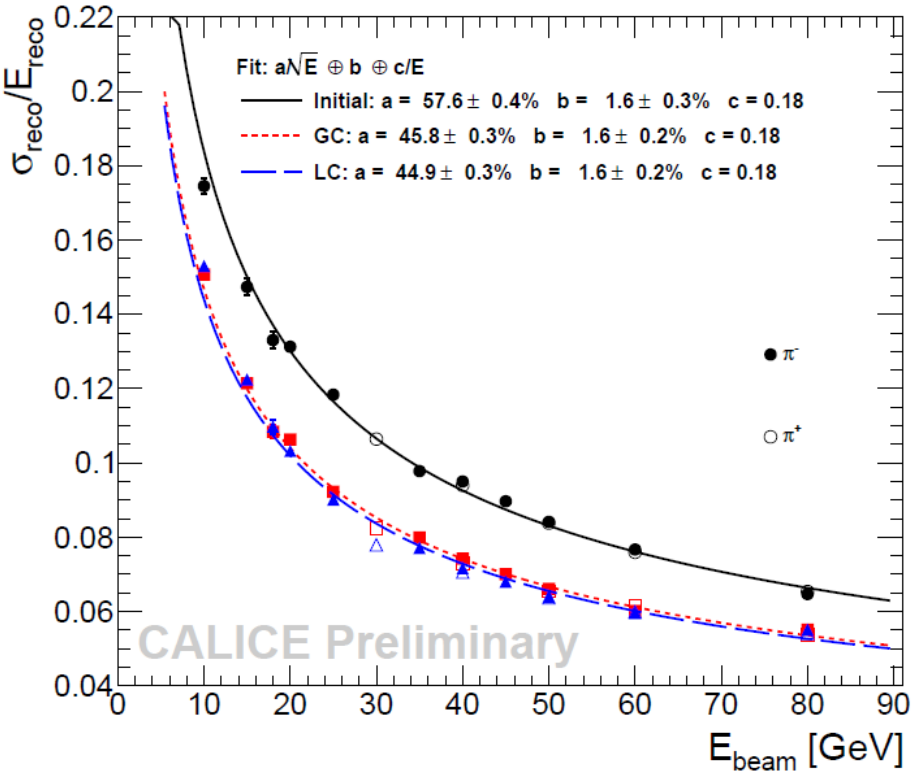
25 GeV pion



Energy resolution

- In spite of imaging capability: Need to measure **shower energy**!
  - → Linearity?
  - → Energy resolution?
- Energy dependent electromagnetic fraction requires **compensation**
  - → Improvement of resolution?

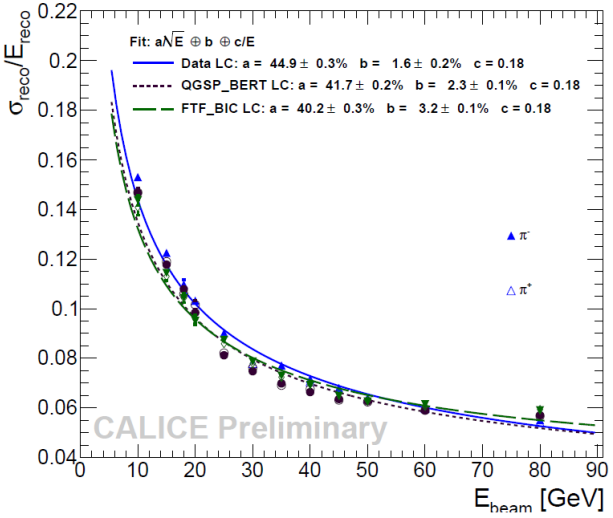


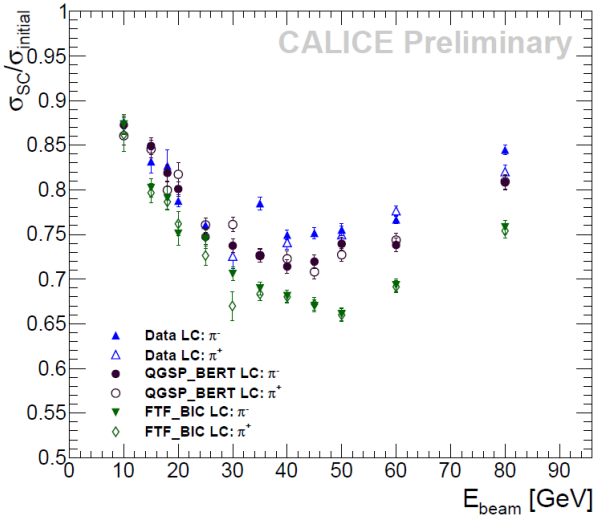


Stochastic term improved from ~58% to ~45%

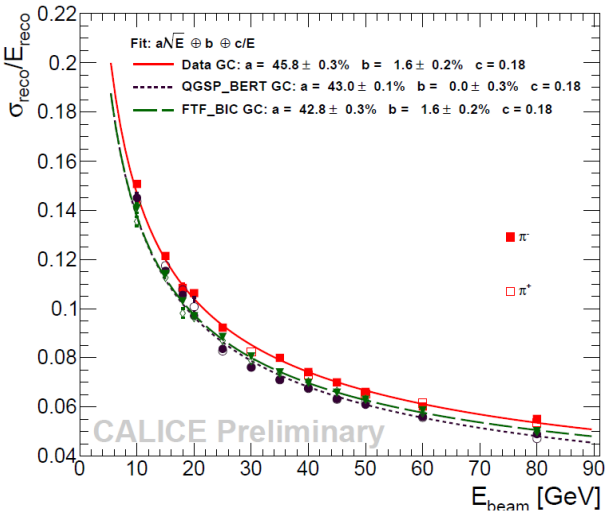
Compensation – MC vs data

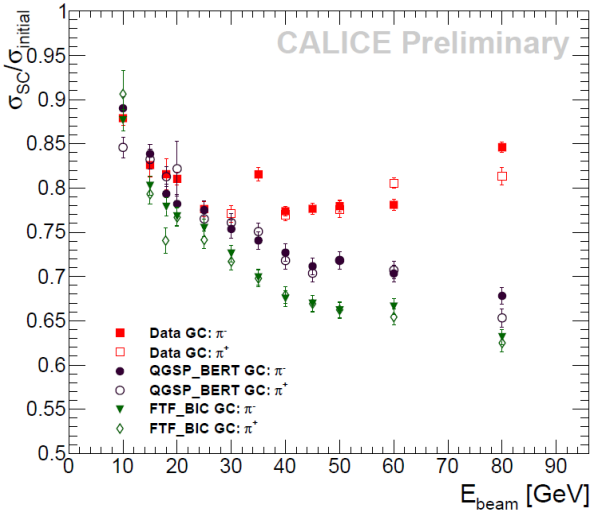
Local compensation





Global compensation





- **Local:**

  MC describes data well

- **Global:**

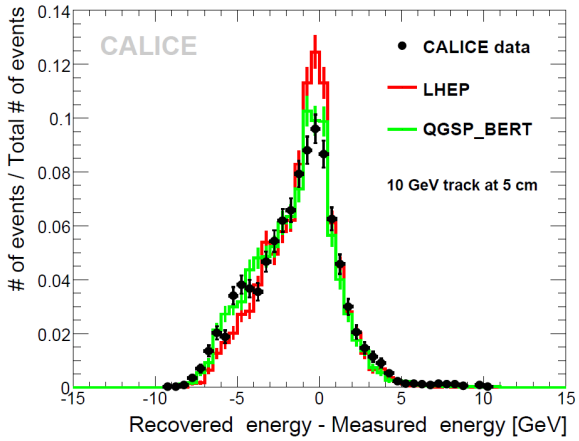
  MC predicts further improvement above 40 GeV

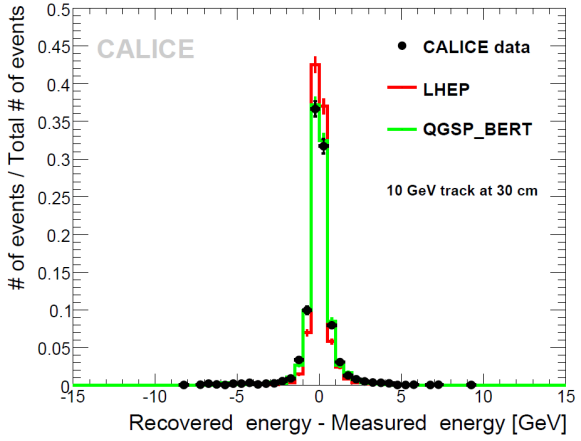
Particle Flow with test beam data

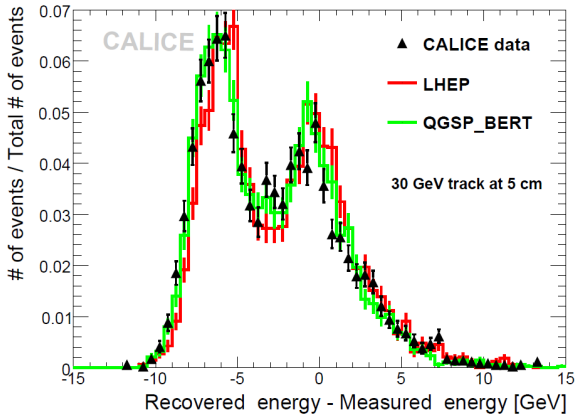
Test MC models with important particle flow analysis!

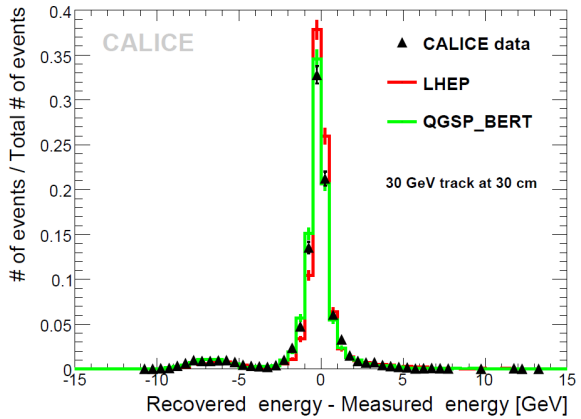
Method:

- Take 2 pion events and map them to ILD geometry
- Assume one is neutral
- Vary distance between the 2 pions and test how well the energy of neutral pion is reconstructed





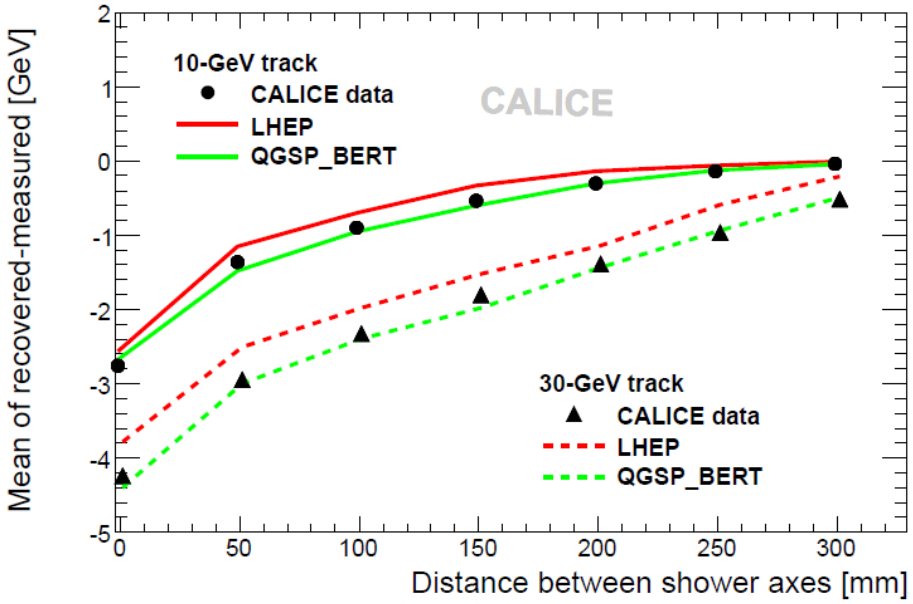


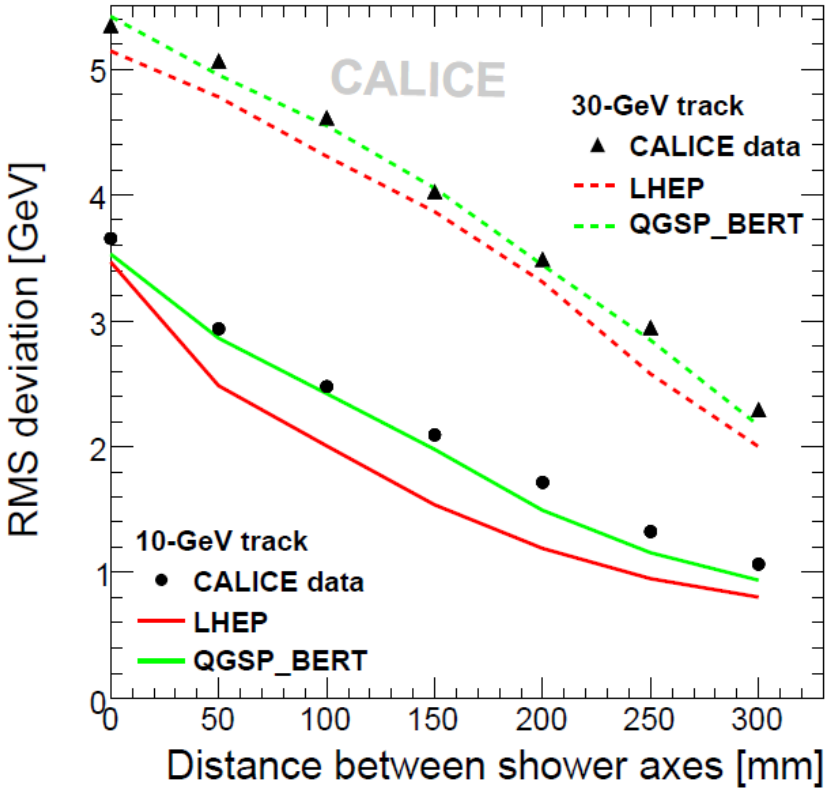


Particle Flow with test beam data

Confusion depends on radial distance between showers and their energy

→ Good agreement between data and MC





Summary

- High granularity of the CALICE analog HCAL offers unique possibility to investigate hadronic showers
- MC application shown for different aspects of data analysis
  - Spatial shower information, shower sub-structure
  - Energy resolution, compensation
  - Application of particle flow algorithm to test beam data
- All german CALICE groups involved in data analysis
- Active collaboration with Geant4 people