Hadronic Showers in a Highly Granular Imaging Calorimeter

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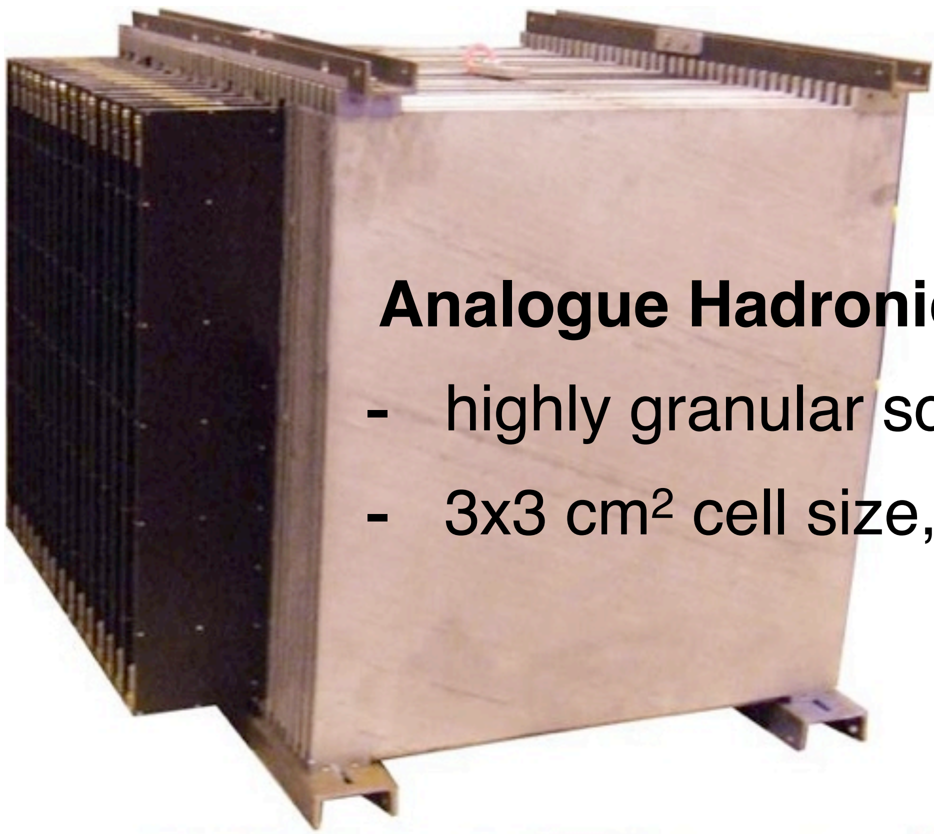
The AHCAL Prototype

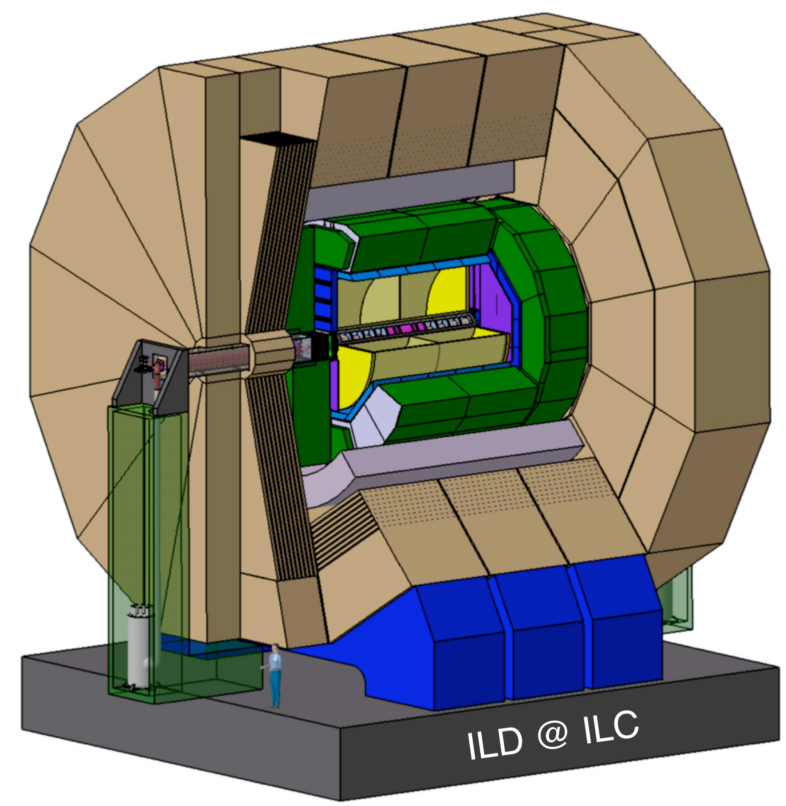
- **CALICE:** calorimeters for precision measurements at future lepton collider, optimized for Particle Flow - aim is a jet energy resolution of:

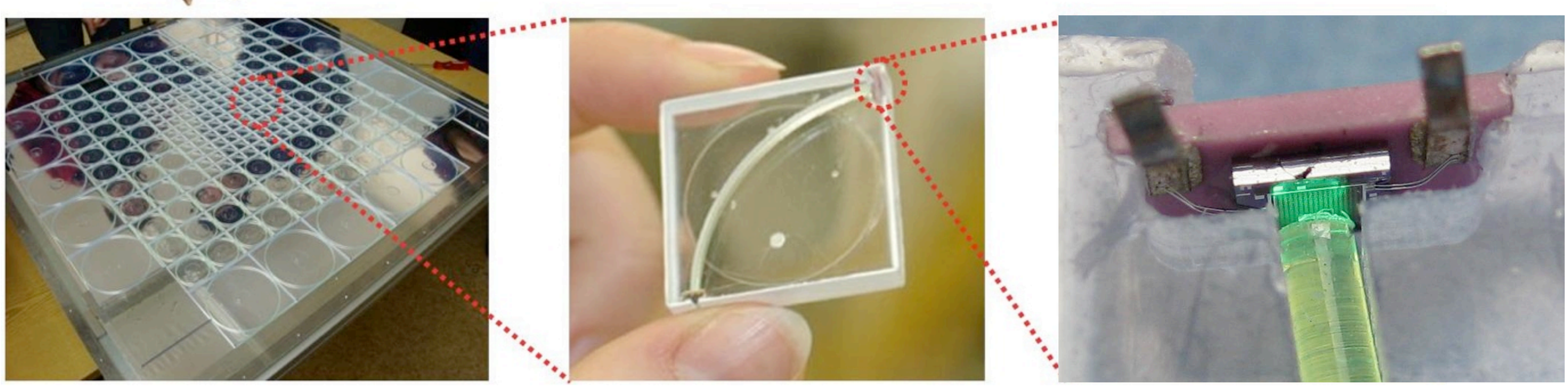
$$\sigma_E/E \approx 3-4\%$$

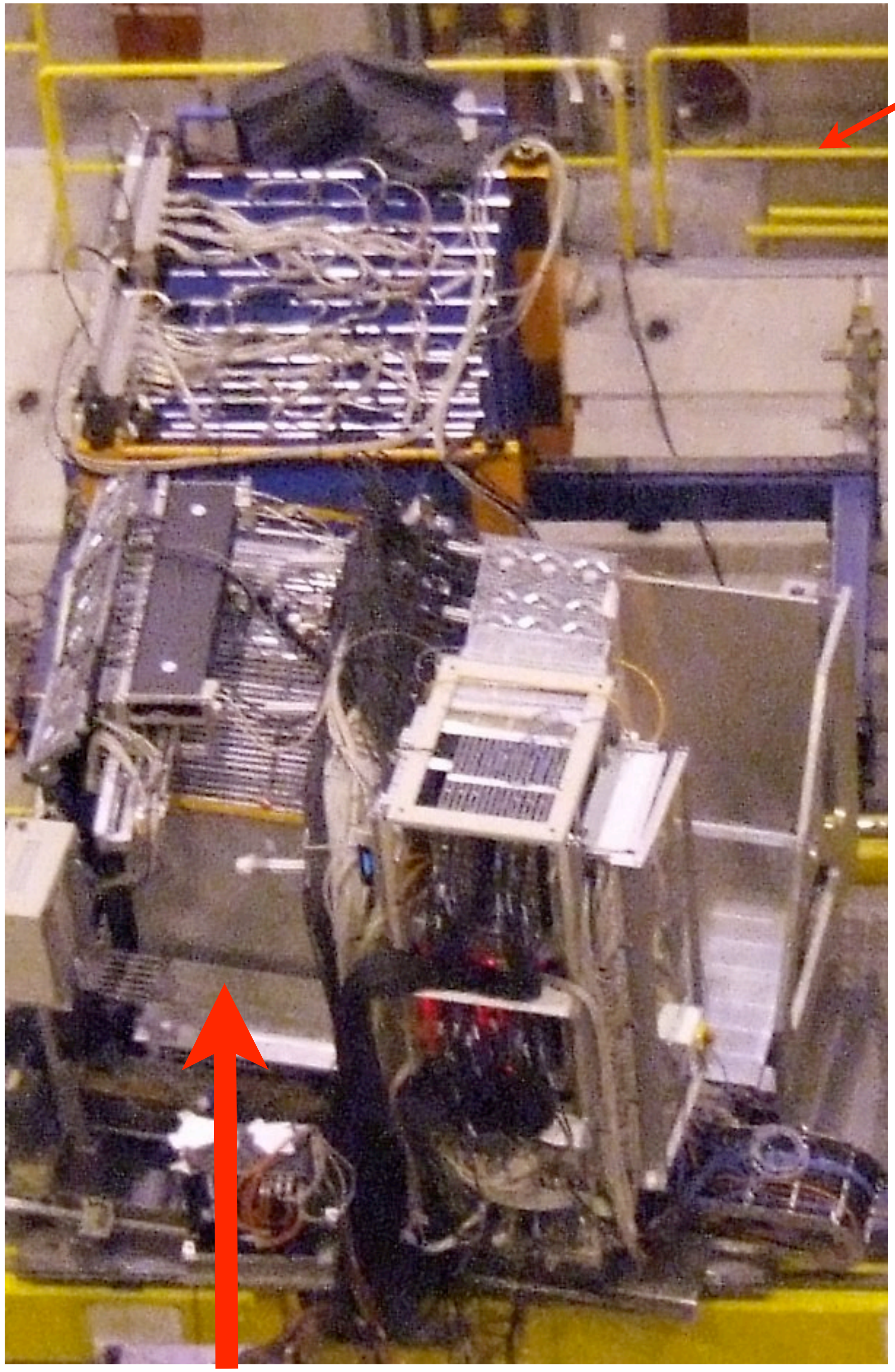


Analogue Hadronic Calorimeter Prototype:

- highly granular scintillator-steel sandwich
- 3x3 cm^2 cell size, 7608 Channels, SiPM readout





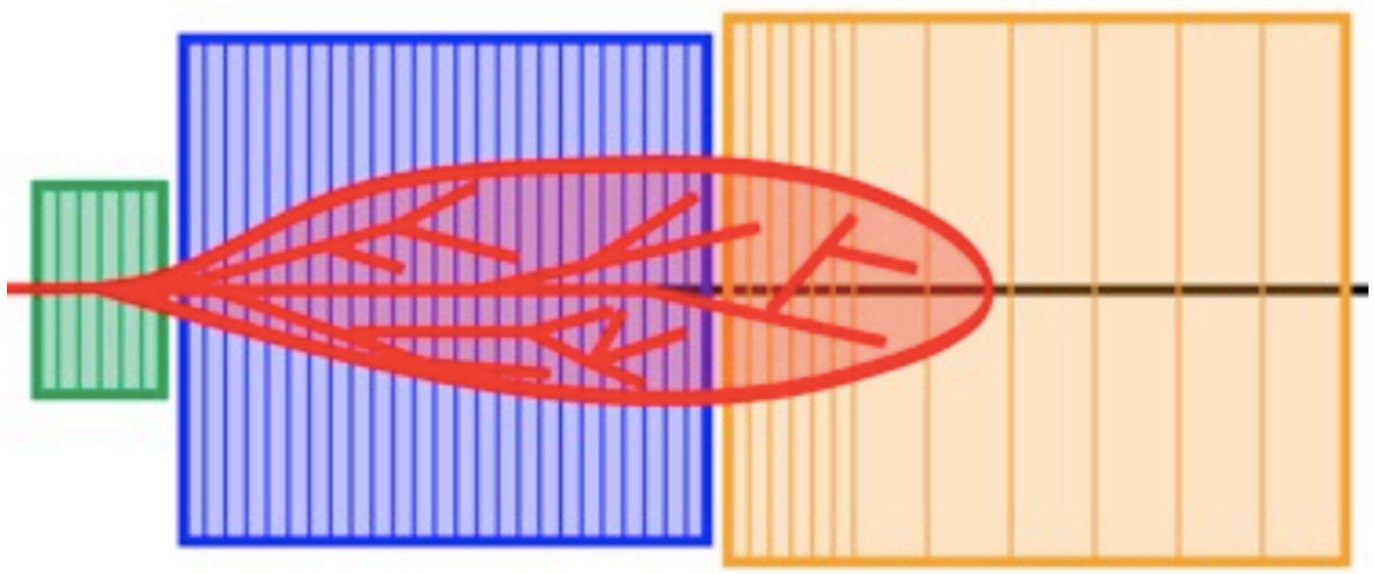


Studies shown base on 2007 CERN data

2006 & 2007: e±, μ and hadron beams 8-180 GeV acquired at CERN SPS H6 test beam

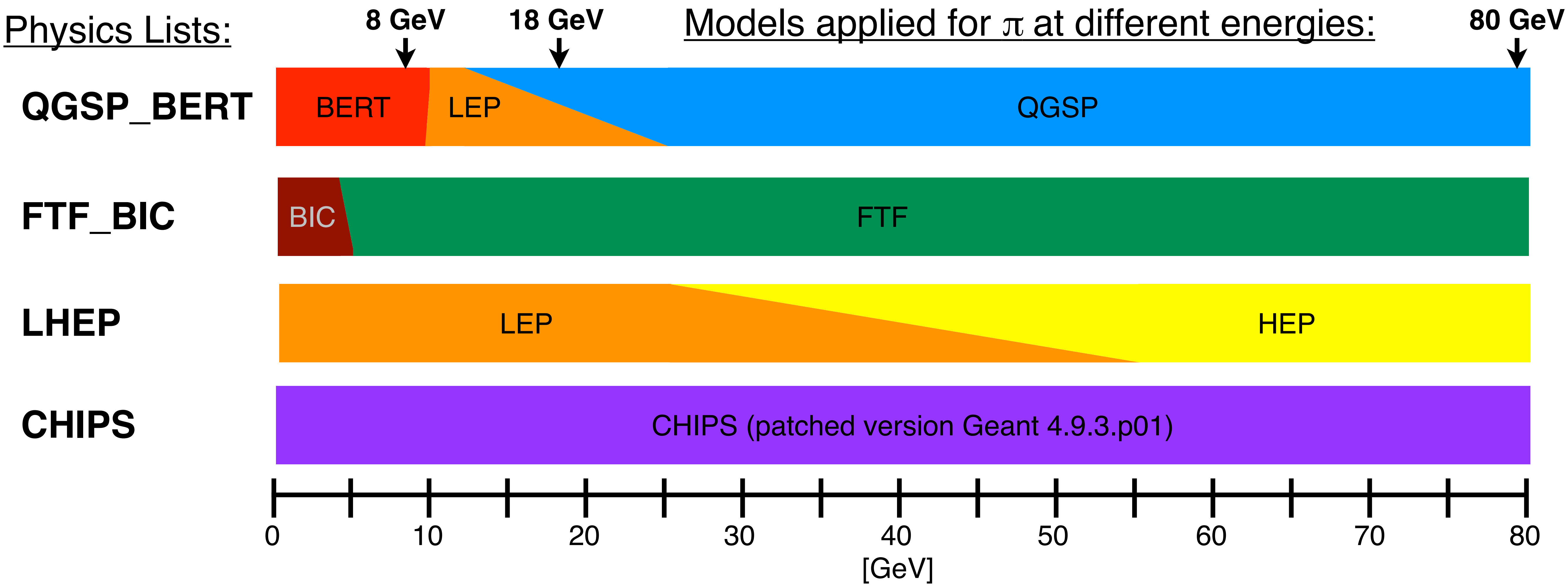
2008 & 2009: extending low energy range from 8 down to 1 GeV at FNAL MTBF

2010 & 2011: active AHCAL layers moved back to CERN: tungsten absorber



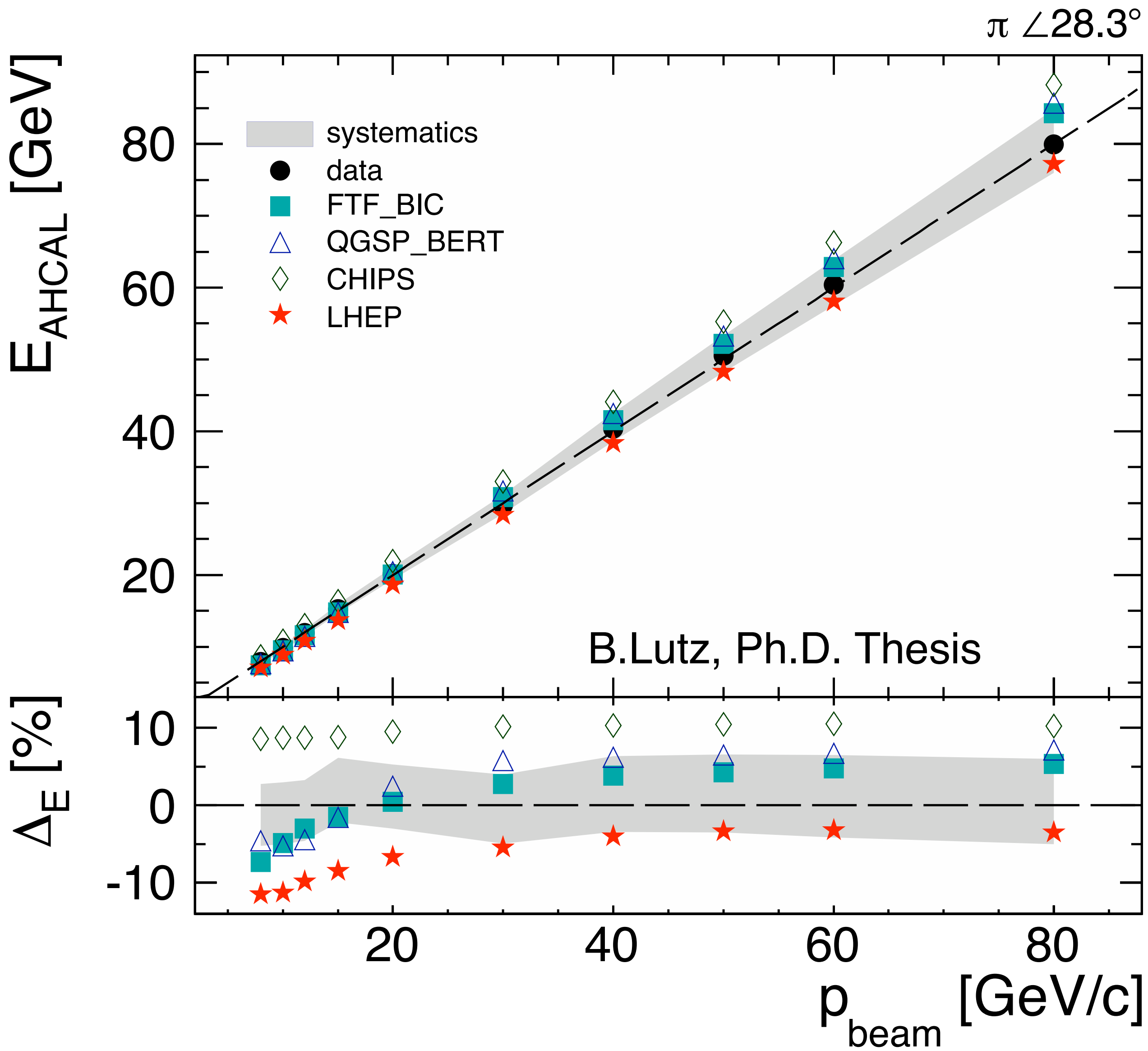
Monte Carlo Simulation

- **Simulation**: necessary for design of real detector, hadronic shower simulation still in development, **validation necessary!**
- **Mokka:** Geant 4 application able to simulate full ILD detector as well as test beam setup
- Geant 4 simulation is organized in **physics lists combining several physics models valid at different energy ranges**. Many physics list tested - here only four presented.
- All Events have been simulated with **Geant 4.9.3**. For simulations with the **experimental CHIPS** physics list the **patched version Geant 4.9.3.p01** was used.

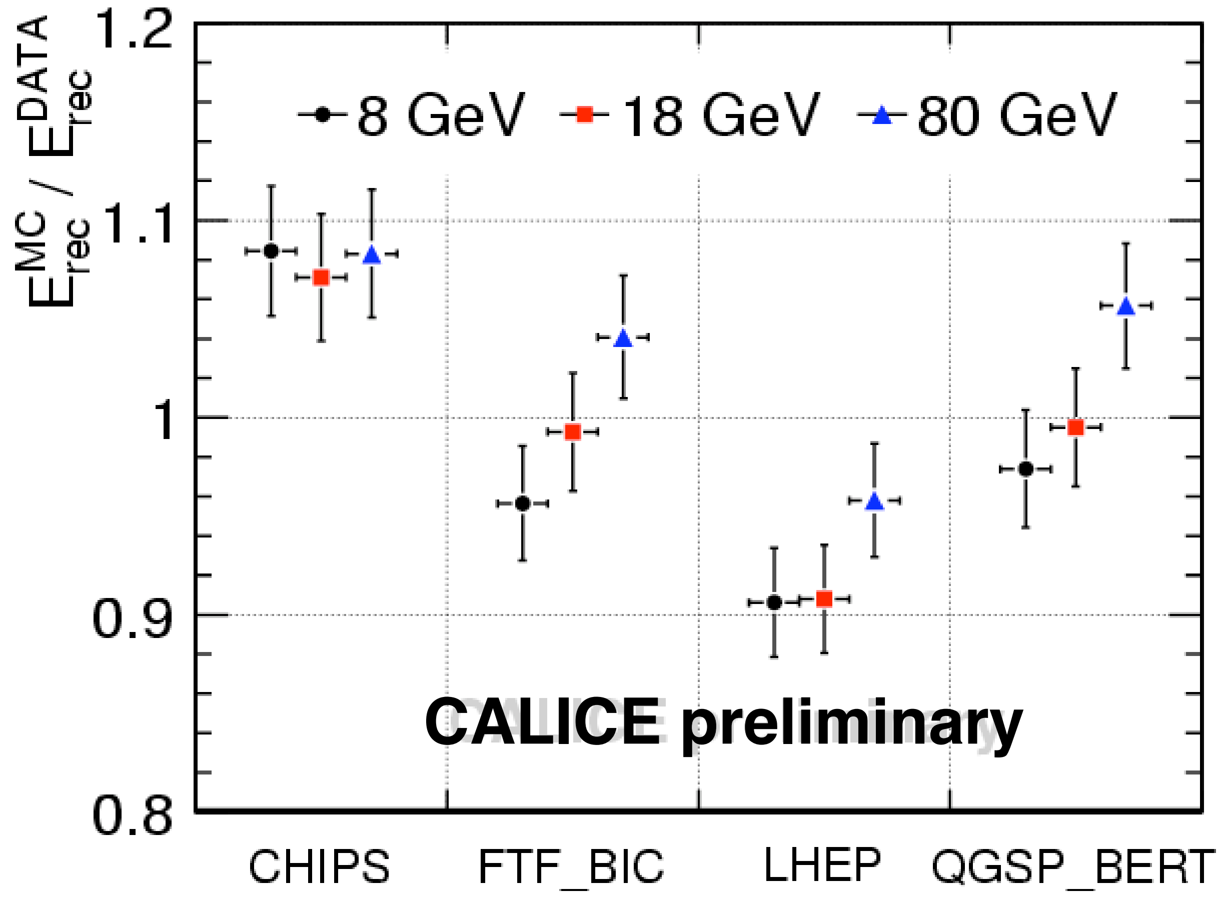


Energy Scale

- First thing to look at to validate calibration and simulations: **Calorimeter Response**



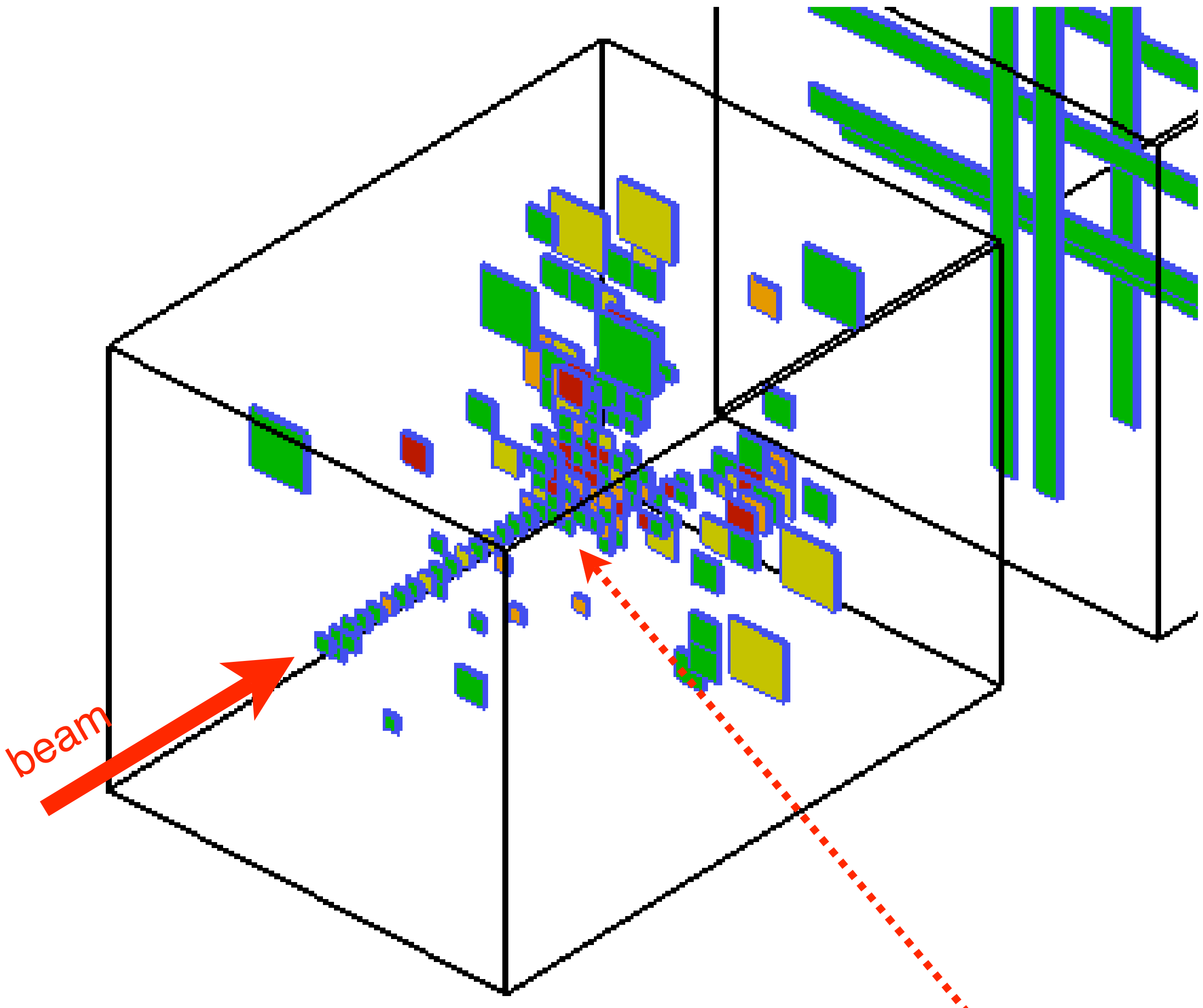
Energy points presented:

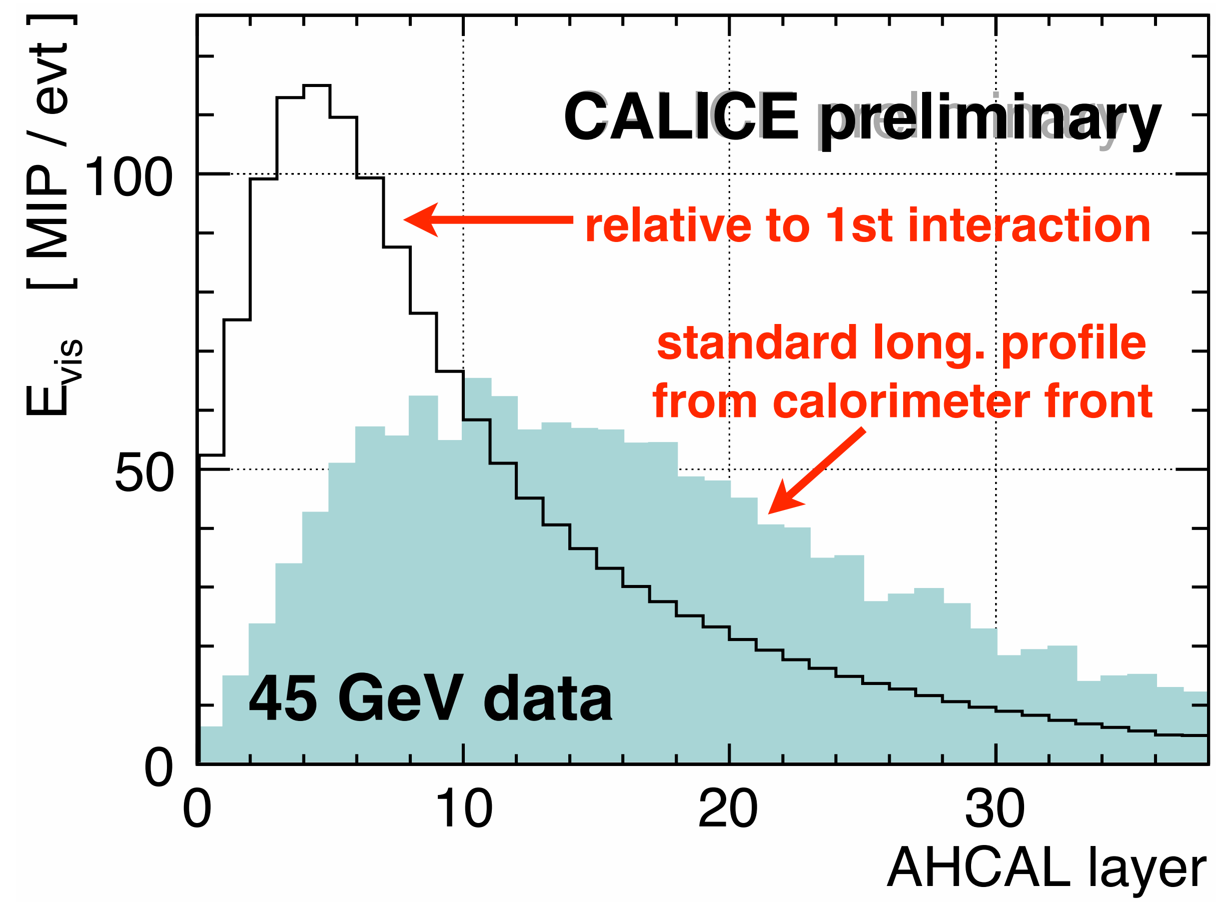


- For **QGSP_BERT**, **FTF_BIC** and **LHEP** the **transition between models is visible.**
- **CHIPS** looks promising - **no transition and no energy dependence**.
  Overestimation of deposited energy is expected due to incorrect simulation of low energy neutrons.

First hadronic Interaction

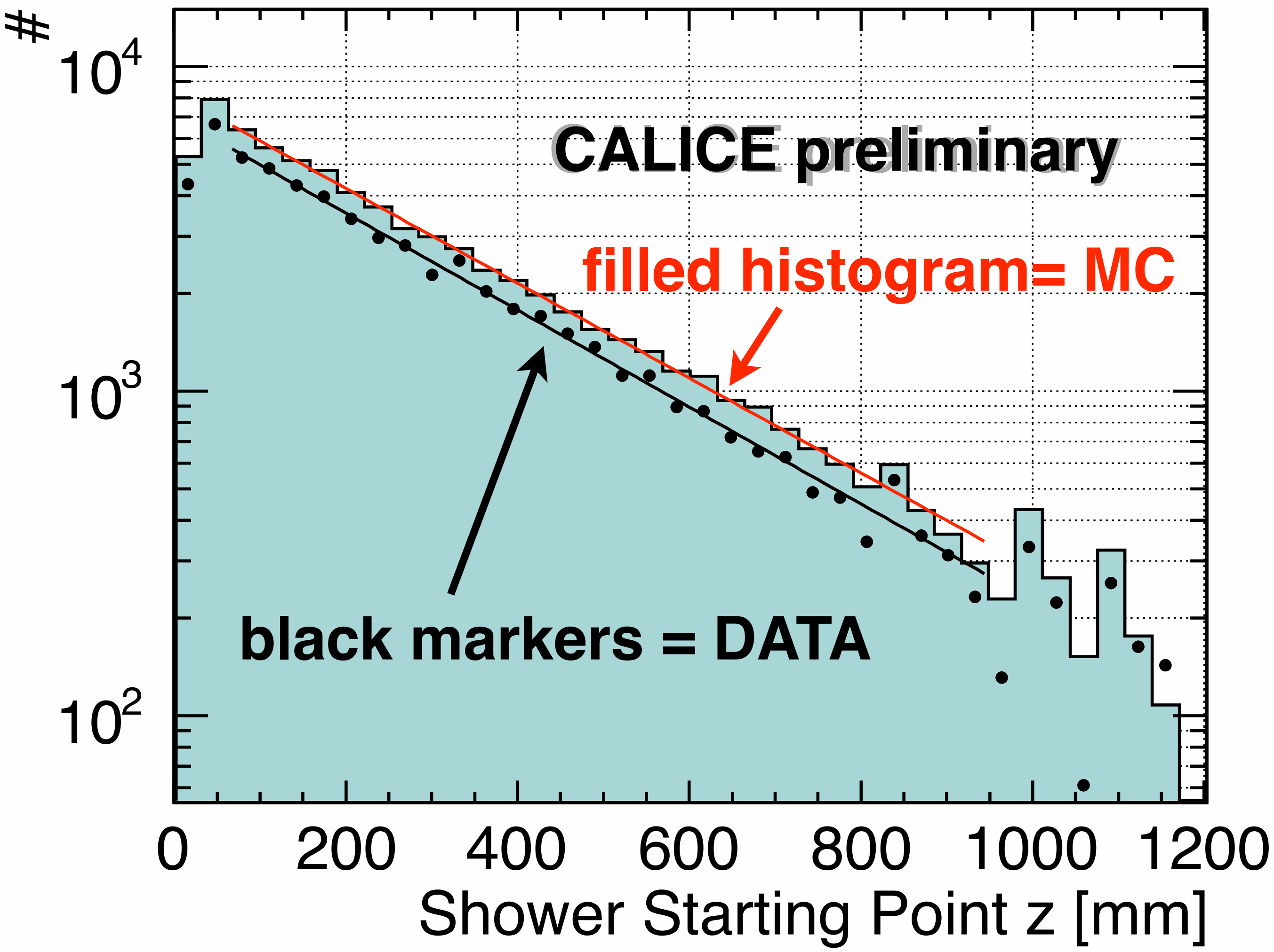
Imaging calorimeter: 20 GeV π shower data

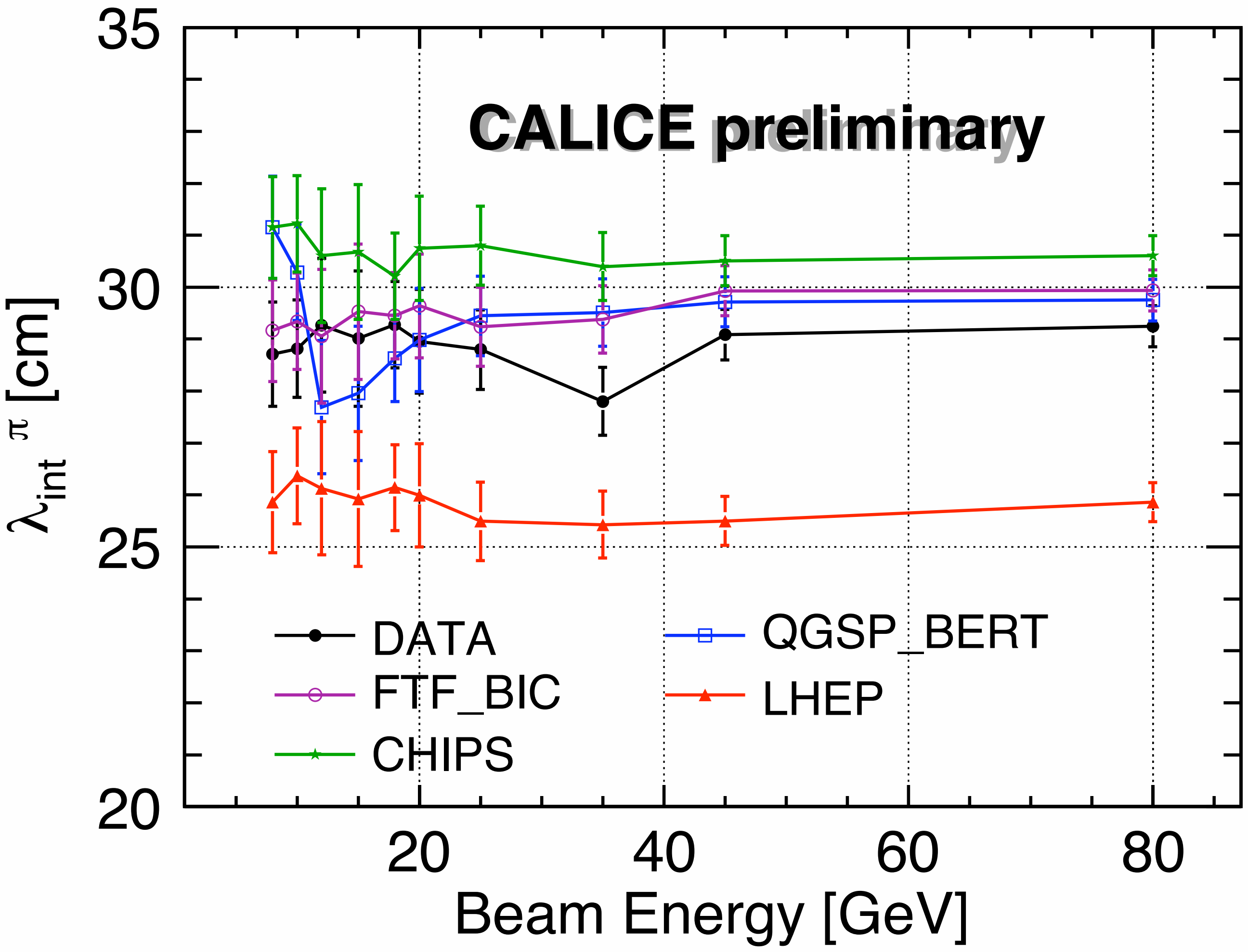




- High granularity allows to find position of first hadronic interaction
- Primary Track Finder by M.Chadeeva: agreement of +/-1 layer for 74% of all events
- Allows shower profiles relative to first interaction point

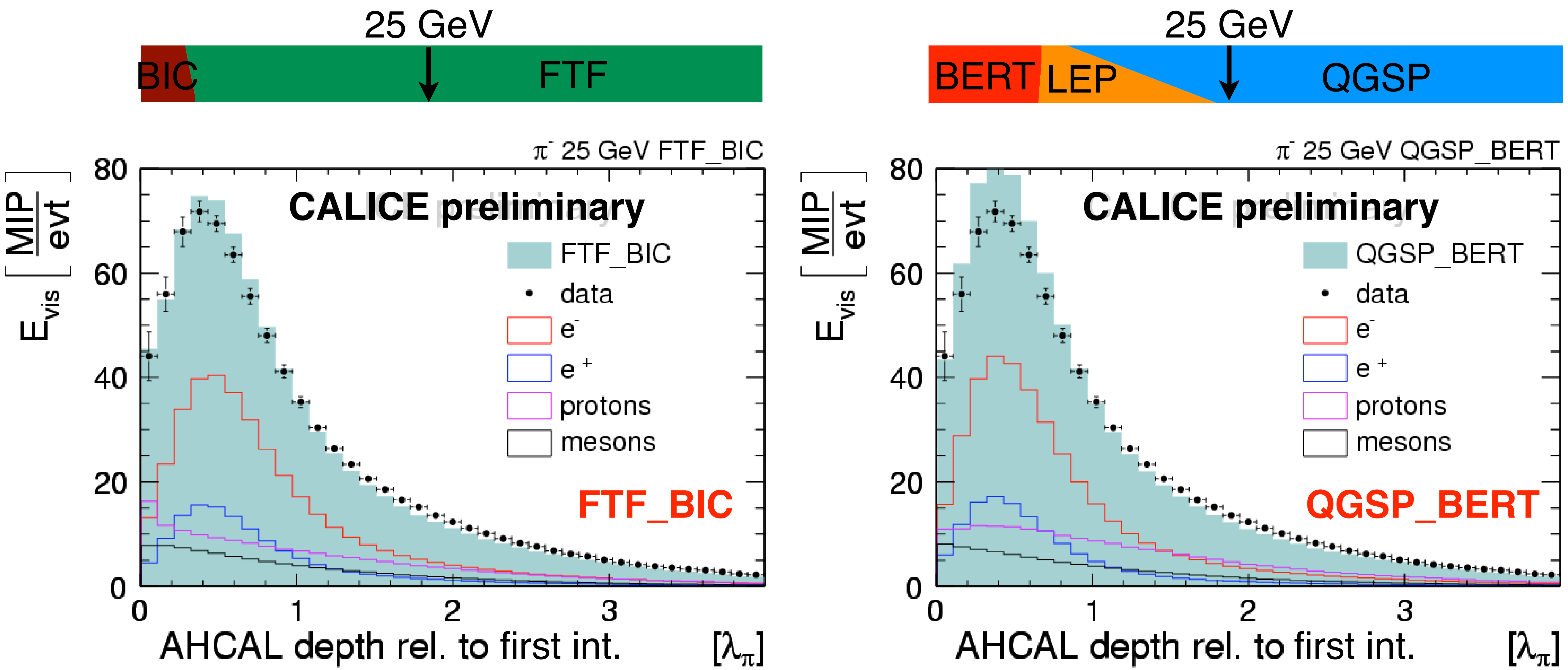
Nuclear Interaction length





- **Distribution of first interaction point: exponential behavior**
- Fitting an exponential (binned-likelihood) allows to extract interaction length for pions
- This is a **test of the cross sections implemented in Geant4**
- FTF_BIC agrees with DATA, for QGSP_BERT transition region is visible - agreement above 20 GeV
- LHEP & CHIPs have both different lambda (expected due to different cross sections)

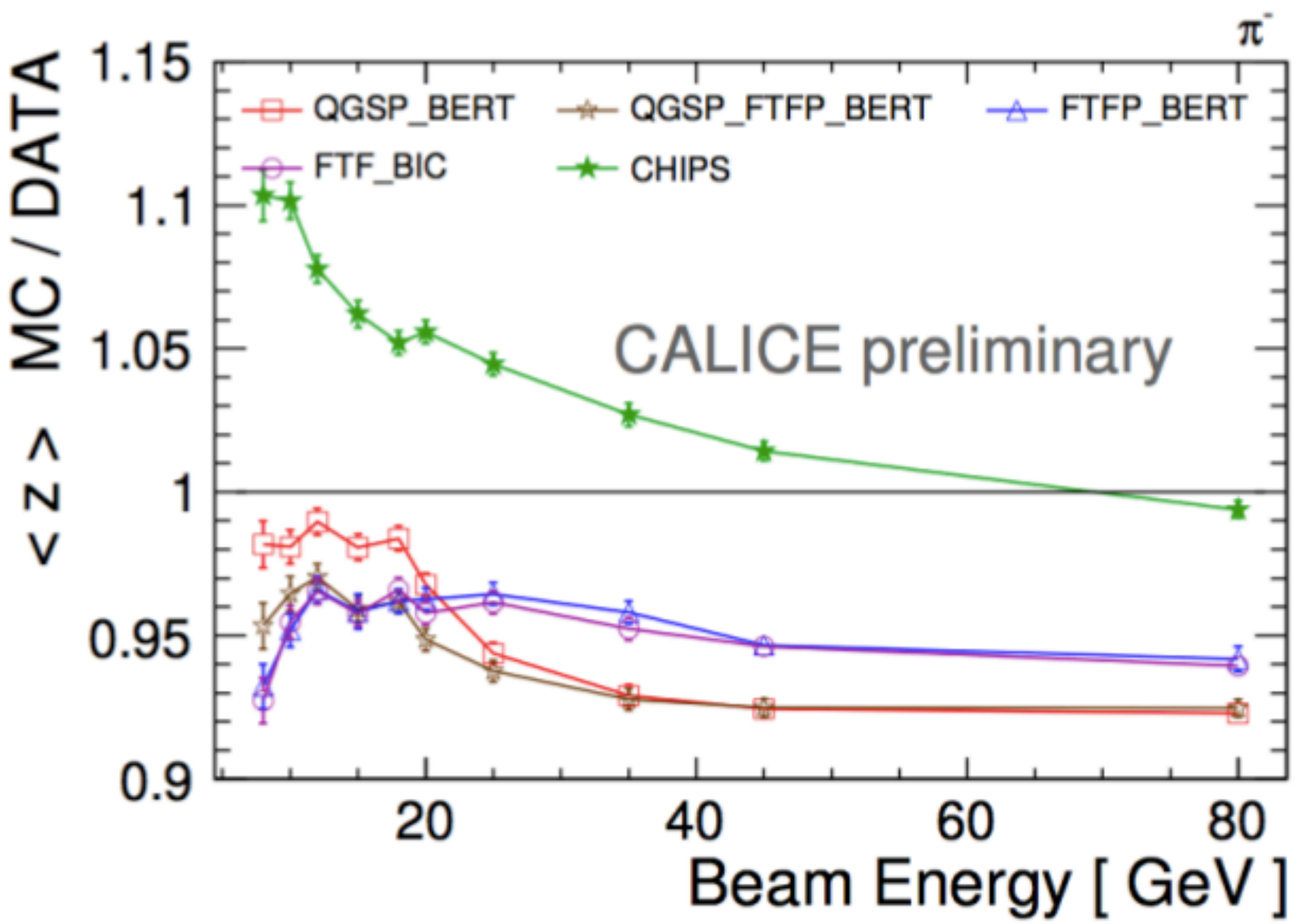
Longitudinal profiles

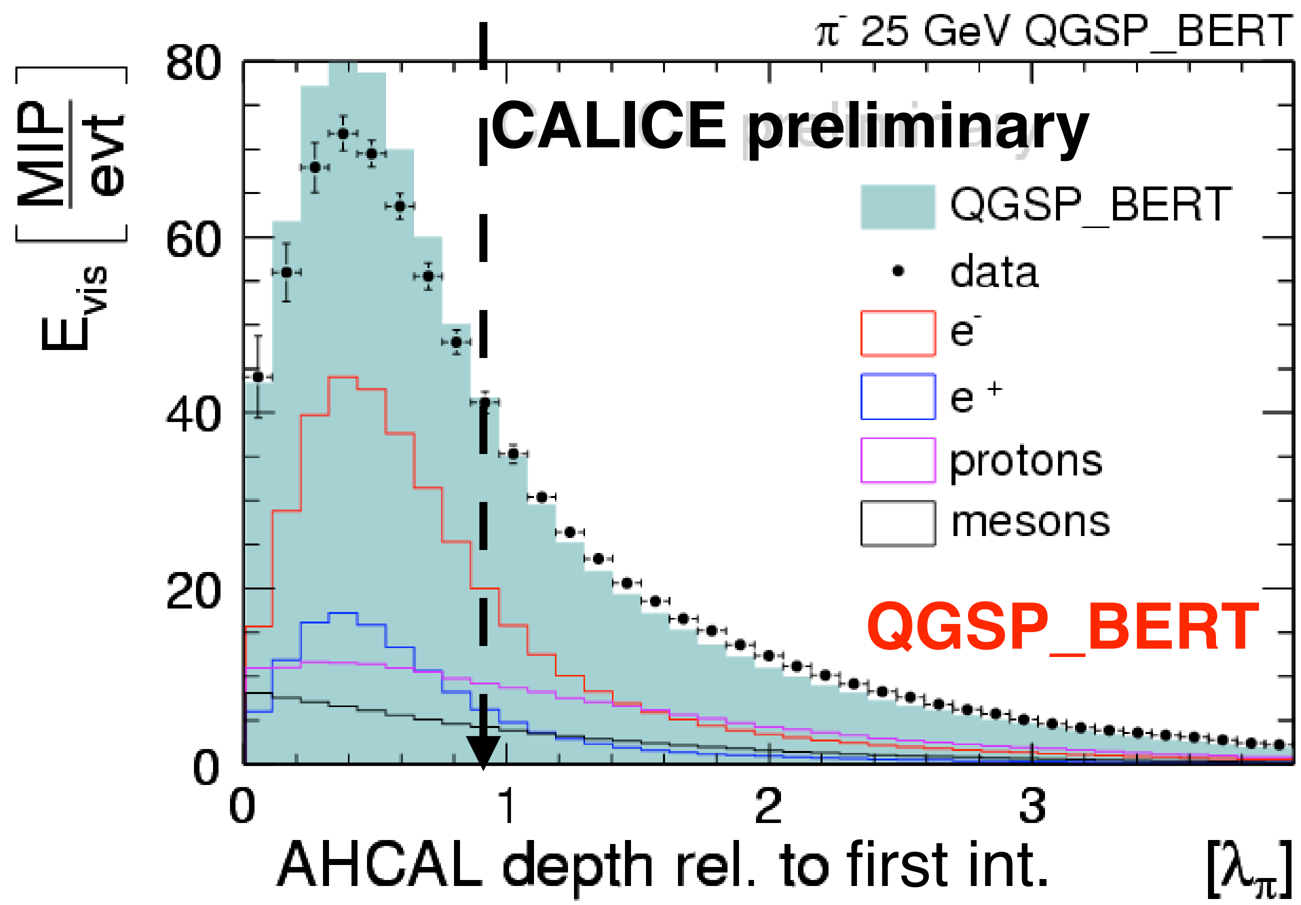


- Profiles relative to first hard interaction point
- Simulation allows to disentangle deposited energy into contributions by electrons, positrons, protons and mesons

Mean Shower Depth

$$< z >= \sum_i z_i E_i \ / \ \sum_i E_i$$

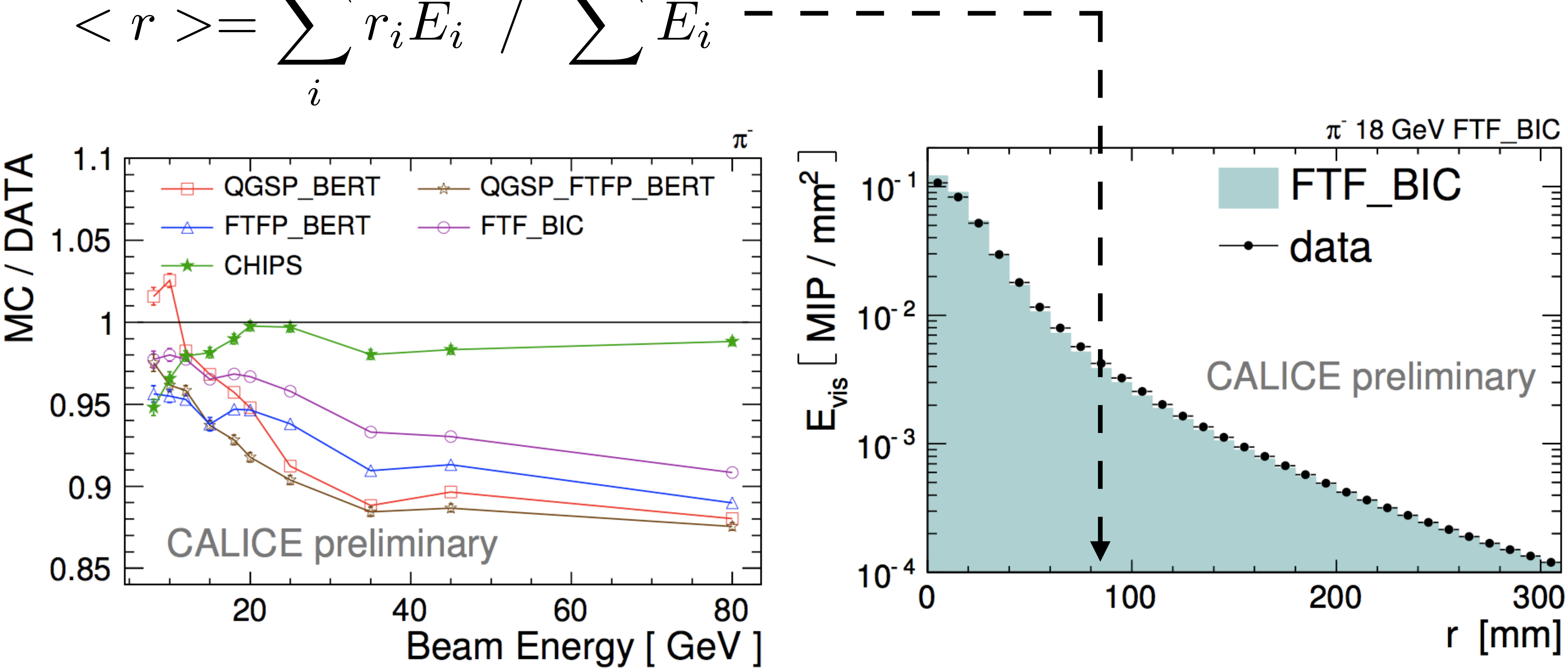




- Fritiof and QGS models predict too small shower depth
- CHIPS shower center of gravity deeper than in data

Mean Shower Radius

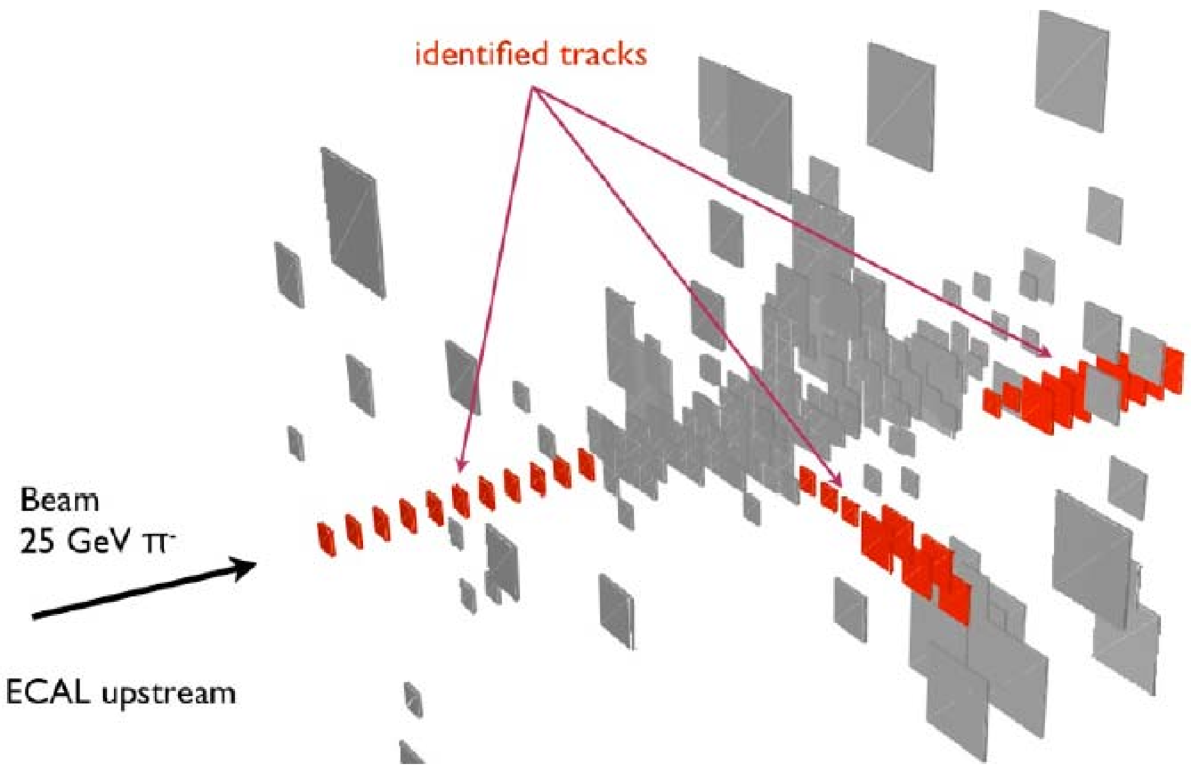
$$< r >= \sum_i r_i E_i \ / \ \sum E_i$$



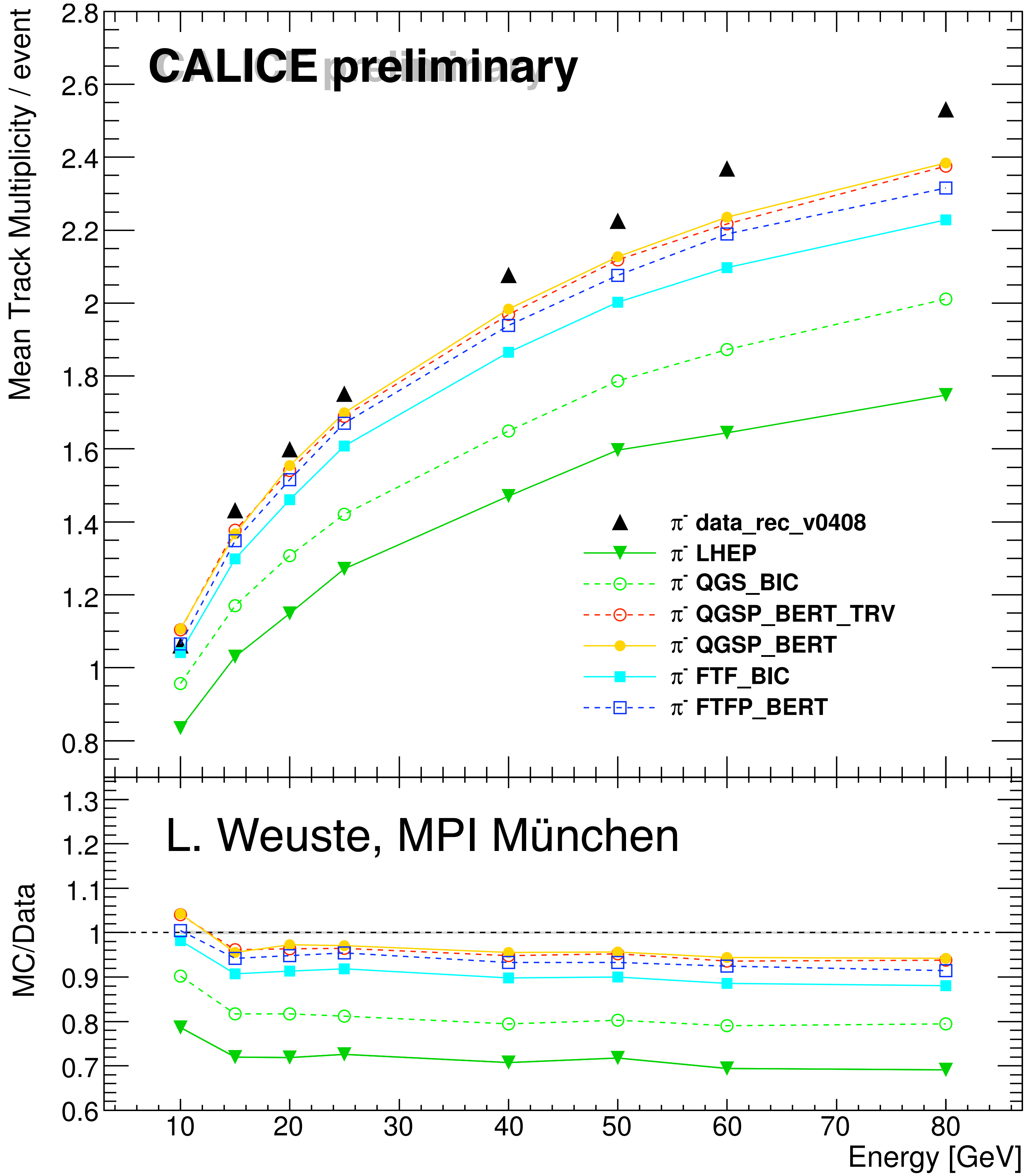
- All models predict too small mean shower radius
- CHIPS model fits best to data

Track segments

Imaging calorimeter: picture of a π shower



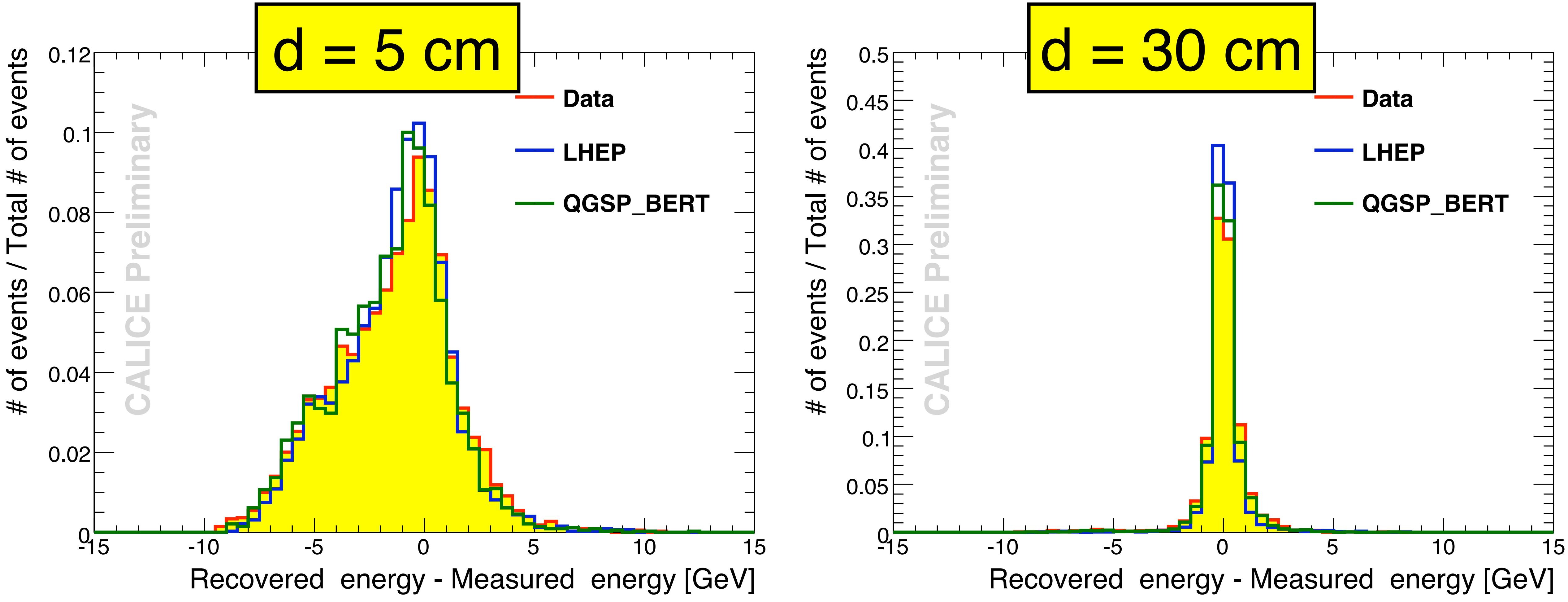
- **Track multiplicity** influenced by shower topology: **number of secondaries created**
- Number of tracks provided by LHEP & QGS_BIC is far too low
- Other lists quite close to each other, from which QGSP is closest to data, FTF_BIC furthest away



Pandora PFA Performance

- Use Pandora PFA with test beam data mapped to ILD geometry
- Overlay two pion showers, assume one to be neutral and the other to be charged
- Investigate PFA performance varying the distance and energy of the two showers

Energy: 10 GeV neutral, 10 GeV charged



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Pandora PFA Performance

- Use Pandora PFA with test beam data mapped to ILD geometry
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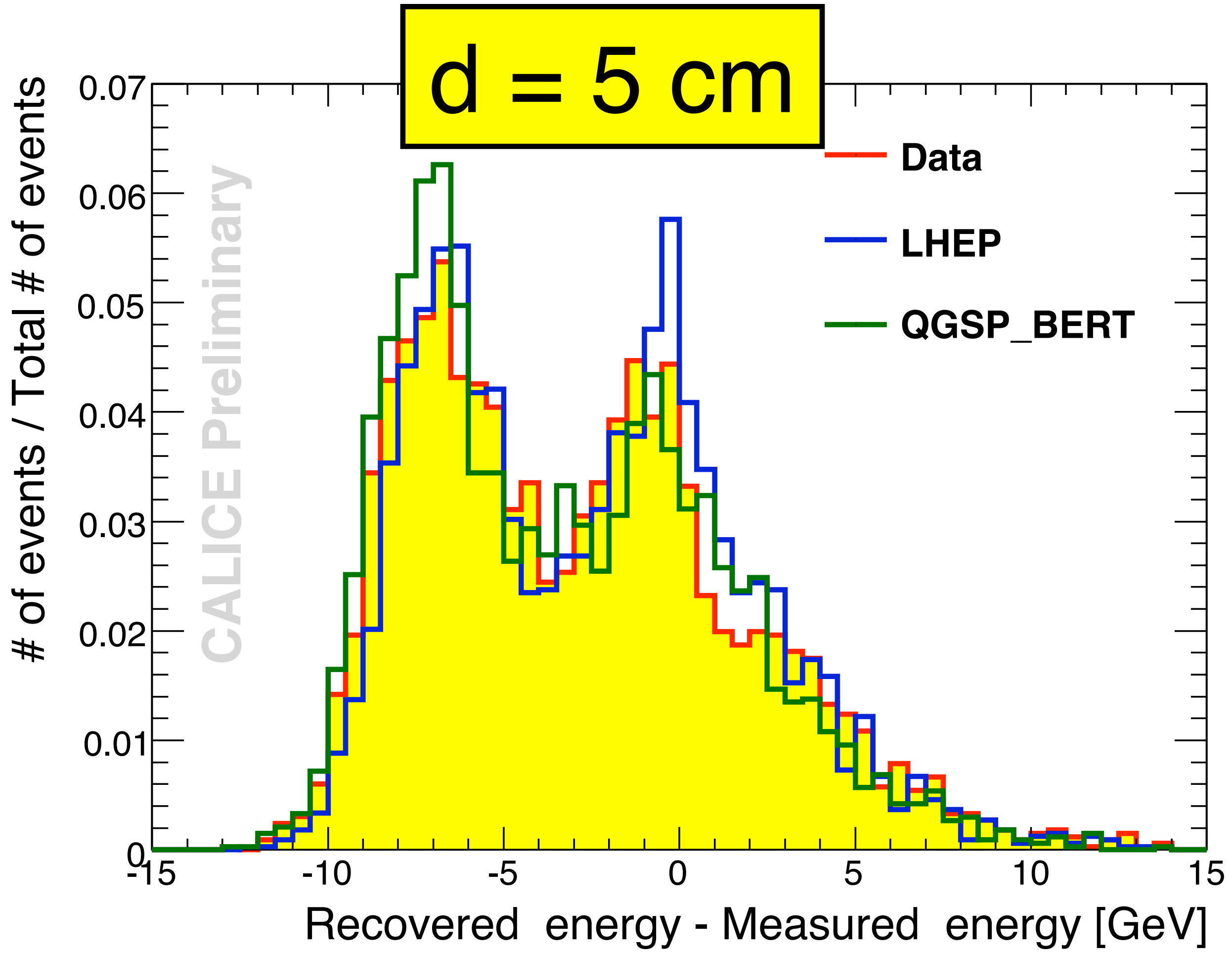
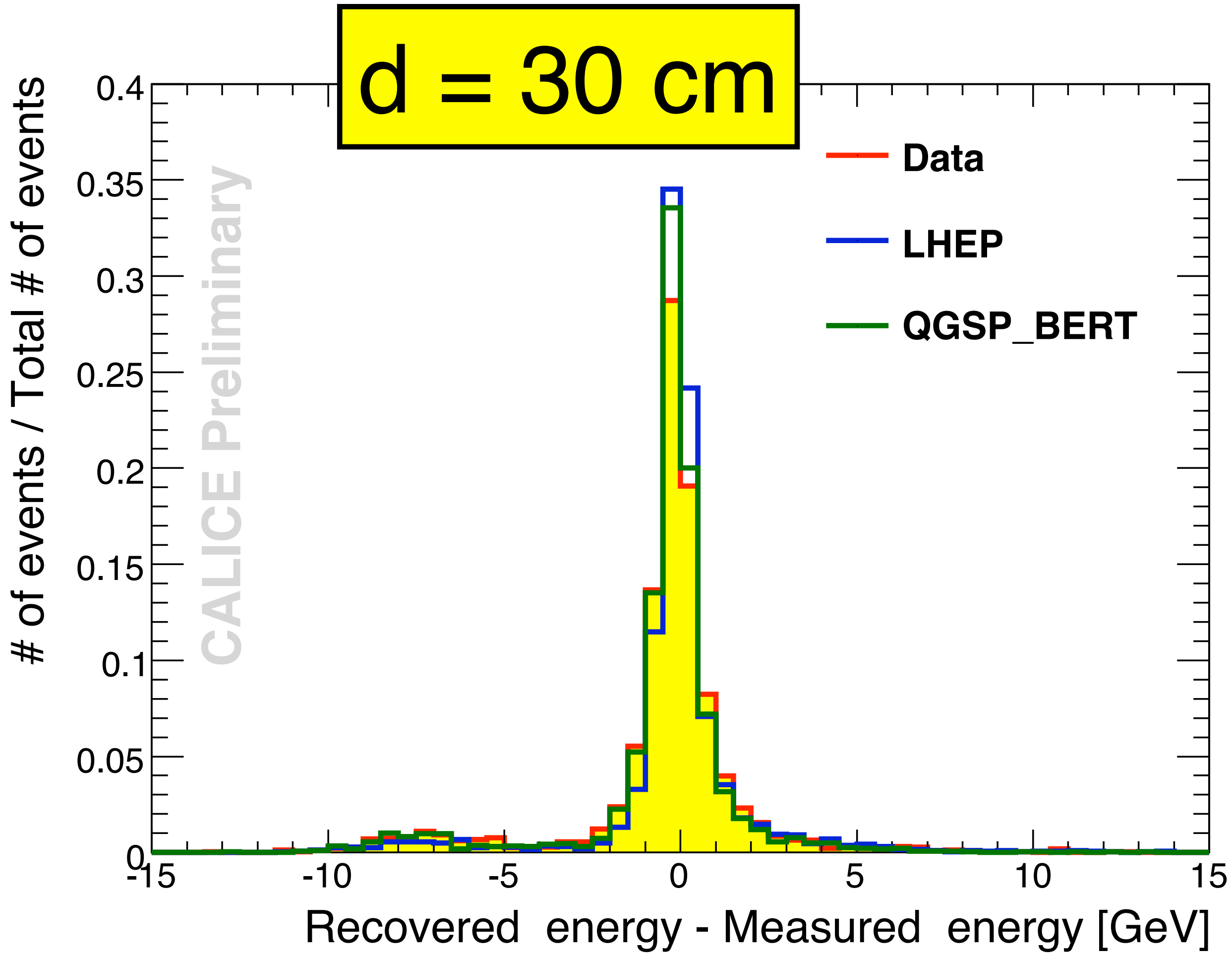
Energy: 10 GeV neutral, **30 GeV charged**





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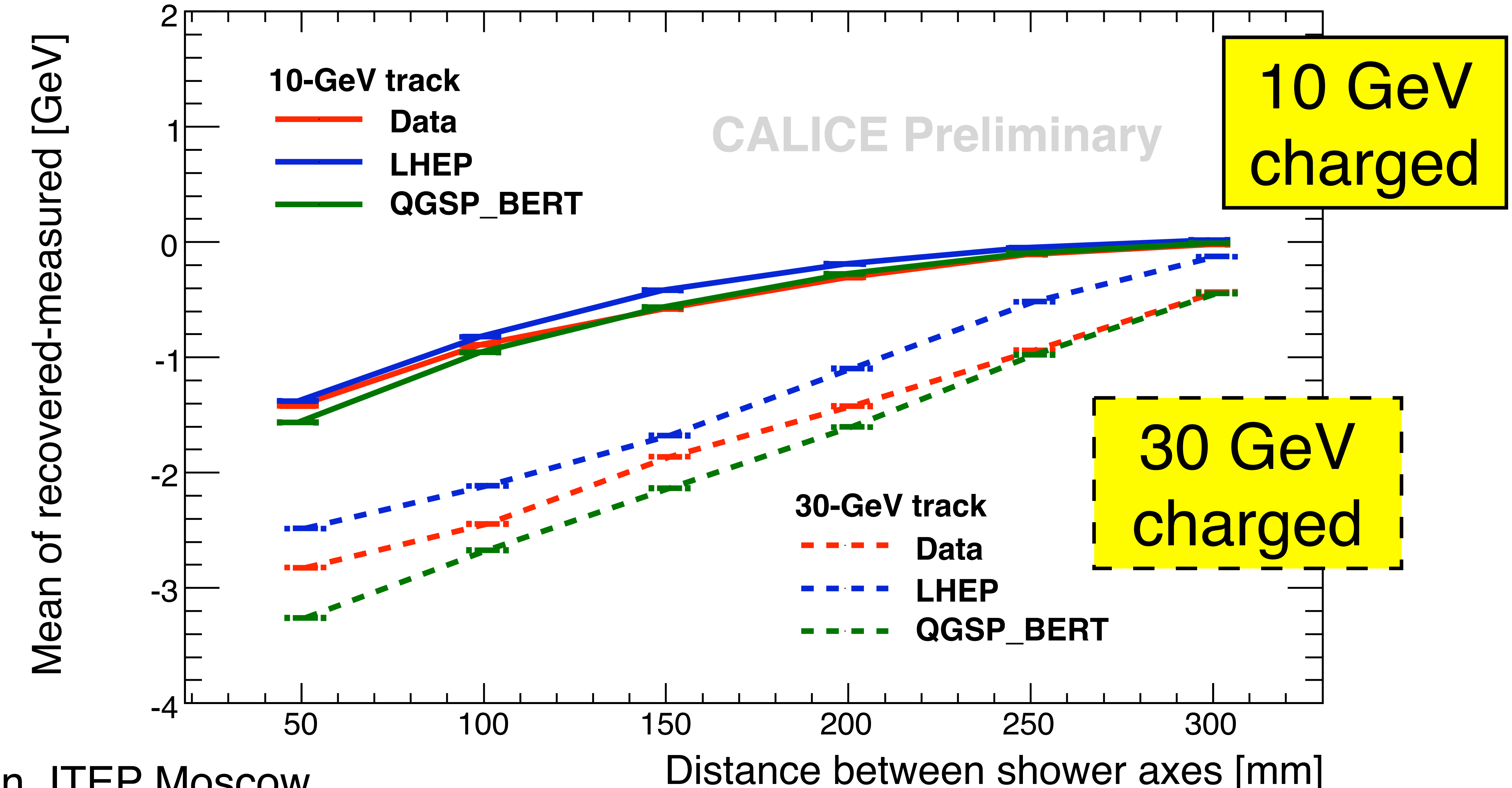

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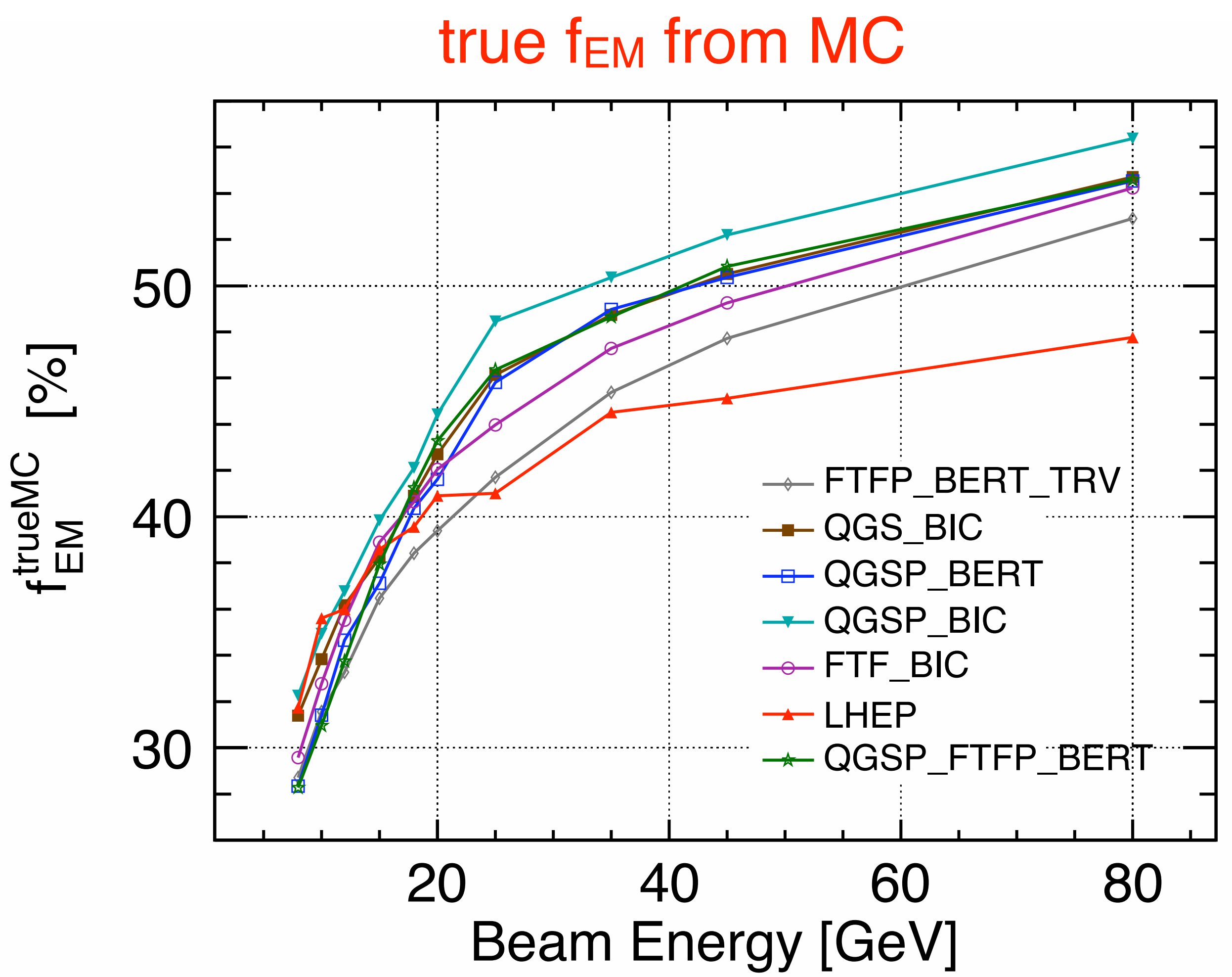
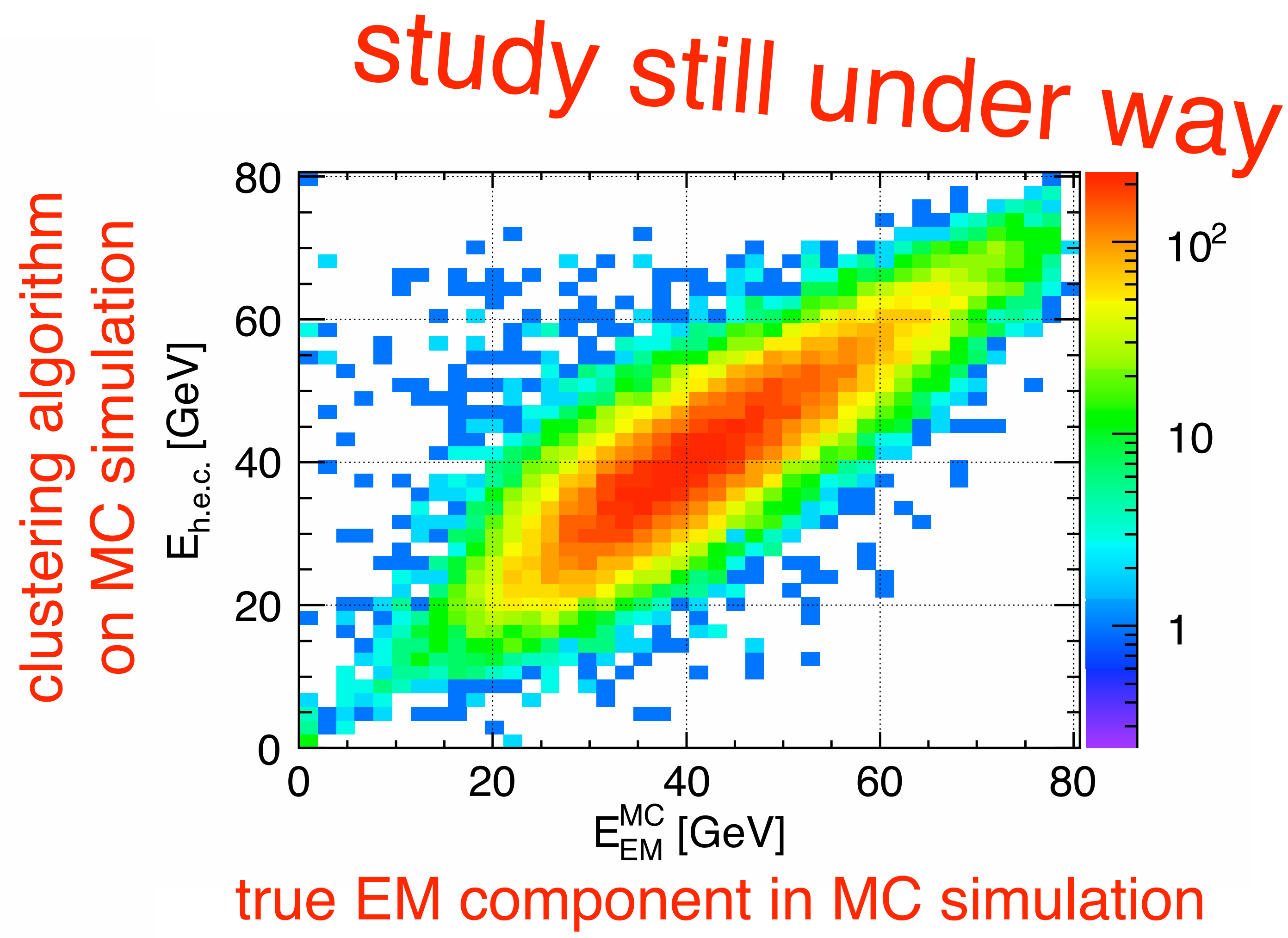
Outlook: EM Fraction





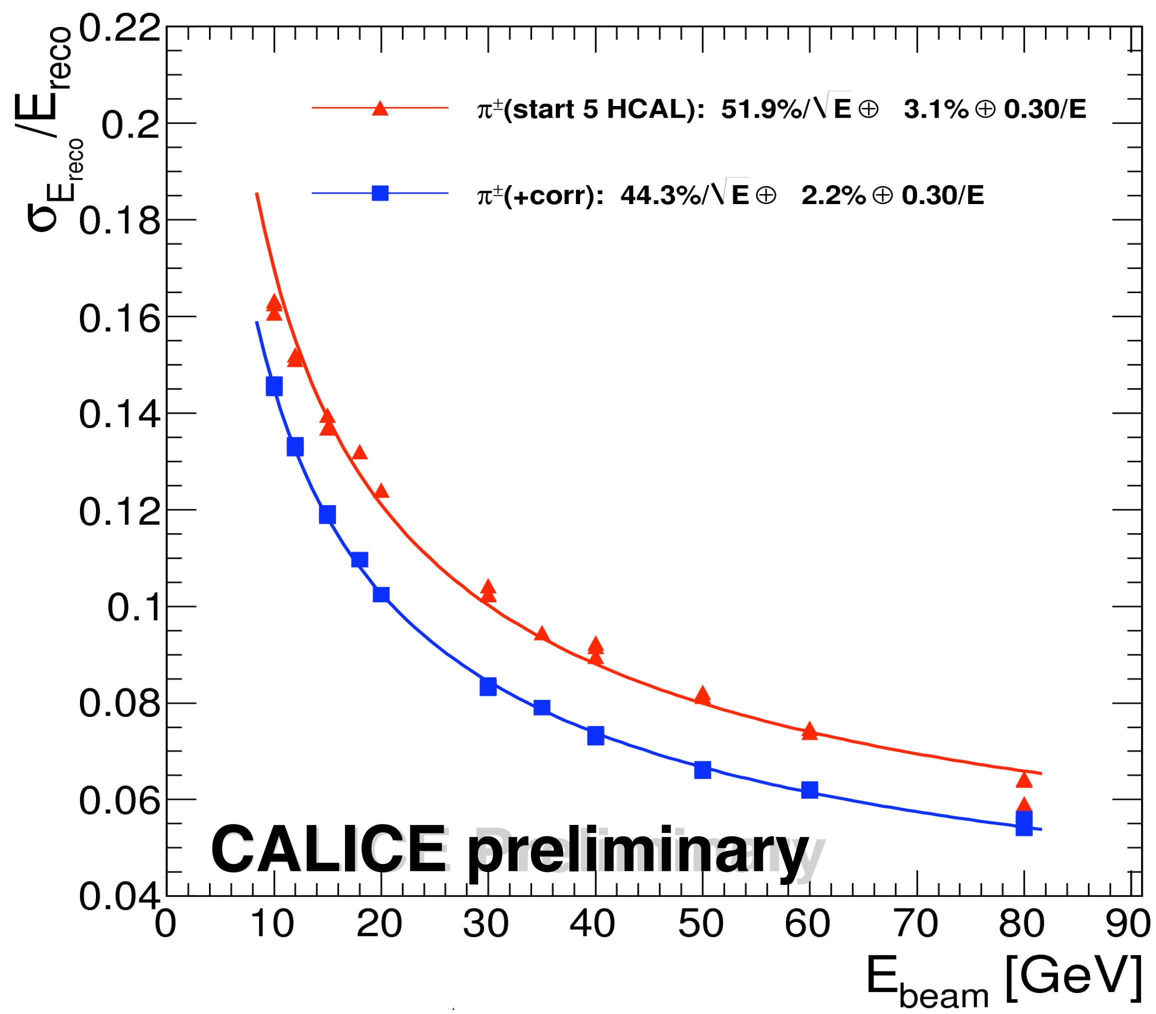
- **EM component = Energy from π^0 and η decaying into γ** → available in MC
- **Simulations show different EM fraction** → validation against DATA interesting
- **Deep Analysis**: clustering algorithm initially developed by V. Morgunov can be tuned to find EM-like clustering → would be also applicable for DATA
- **Not ready yet**: cluster identification still energy and physics lists dependent has to be improved further.

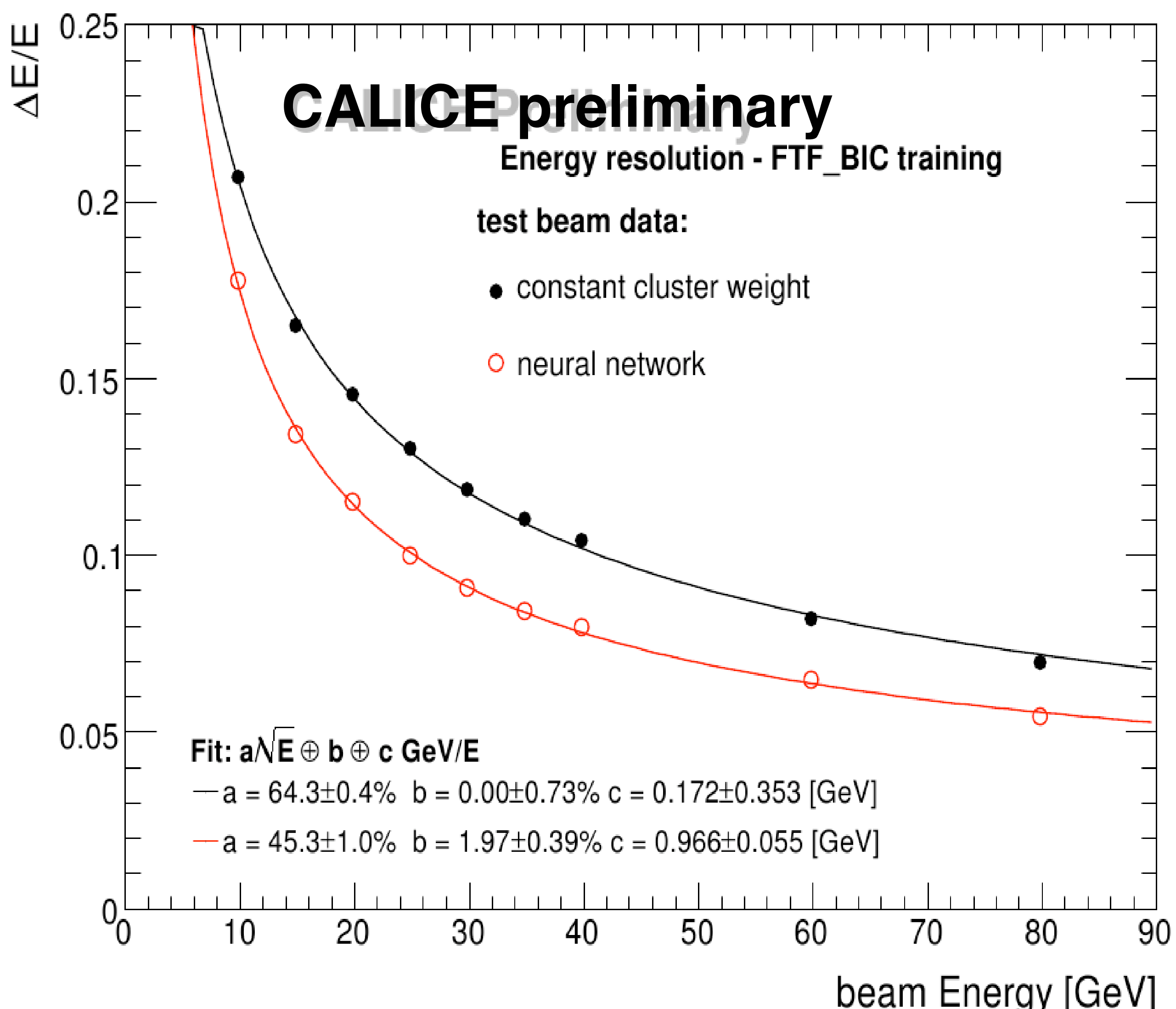
Summary

- The CALICE collaboration built a **highly granular analogue hadron calorimeter**
- It allows **precise measurements of hadron showers** as well as **validation of MC models** on a very precise level
- **Imaging calorimeter**:
  - measure track multiplicity
  - determine first interaction point
  - PFA validation with test beam data
  - possibly measure EM component in data (in progress)
- **Conclusion on physics lists:**
  - LHEP: outdated, shown for reference since it is still used as stop gap
  - String + Cascade models: give reasonable description, but room for improvement
  - CHIPS model: promising, but still experimental - patched version 4.9.3.p01 tested

ADDITIONAL SLIDES

Energy Resolution





- Resolution without any compensation: $\approx 52\%/\sqrt{(E)}$
- High granularity allows software compensation approach - several methods studied
- Basic idea is, that **EM-components of shower are denser**
  → use an event-wise weighting of hits to energy density
  → typically achieve a relative improvement of 10-20%
- Geant4 physics lists model this reasonable well, but not perfectly