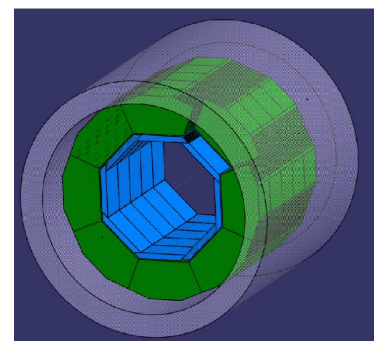
CALICE Test Beam Data and Hadronic Shower Models

Riccardo Fabbri

on behalf of the *CALICE* Collaboration

EUDET Annual Meeting **Geneva, 19 October 2009**

- **CALICE and Calorimeters**
- **AHCAL Response to Positron Showers**
- **Investigation of Hadron Showers**
- **Monte Carlo Comparison with Data**
- **Including the ECAL in Hadron Analysis**
- **Conclusions and Outlook**



The CALICE Collaboration

- **CALICE: ≈ 300 physicists/engineers from 53 groups in 17 countries**
- **Investigate/develop options for high granularity calorimeters**

  $\Rightarrow$ **demonstrate feasibility of Particle Flow Approach for a future Linear Collider detector**

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- **CALICE: ≈ 300 physicists/engineers from 53 groups in 17 countries**
- **Investigate/develop options for high granularity calorimeters**

  $\Rightarrow$ **demonstrate feasibility of Particle Flow Approach for a future Linear Collider detector**
- **Focus given to combined Drift_Chambers + ECAL + HCAL + TCMT test-beam operations, in common DAQ/Analysis framework**
- **Test beam goal:**

  $\Rightarrow$ **establish technology to use**

  $\Rightarrow$ **tune the reconstruction algorithms**

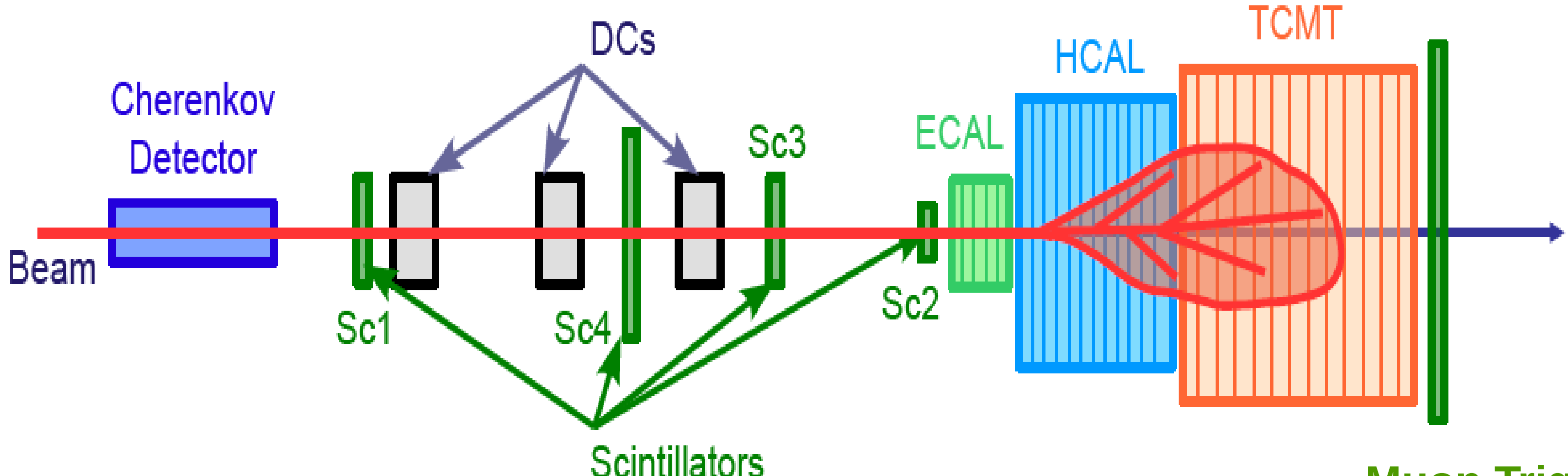
  $\Rightarrow$ **validate/tune Monte Carlo models**

CALICE Test-Beam Program

Main combined physics run with $\mu, e^{\pm}, \pi^{\pm}$ beams:

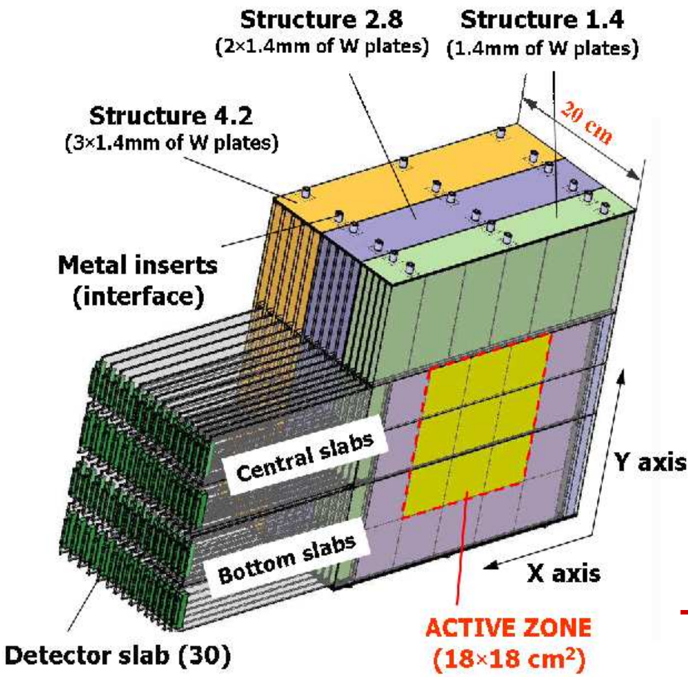
- **2006-07**
  - — **SiW ECAL + AHCAL + TCMT @CERN**
- **2008**
  - — **SiW ECAL + AHCAL + TCMT @FNAL**
- **2008-09**
  - — **W/ScintStrip ECAL + AHCAL + TCMT @FNAL**
- **2010 (planned)**
  - — **SiW ECAL + DHCAL + TCMT @FNAL**

The results presented here concern the investigation of hadron showers using the CALICE 2007 data, mainly AHCAL data



CALICE Detectors Setup: 2007

ECAL



— SiW sandwich structure

— 30 layers of 3x3 modules

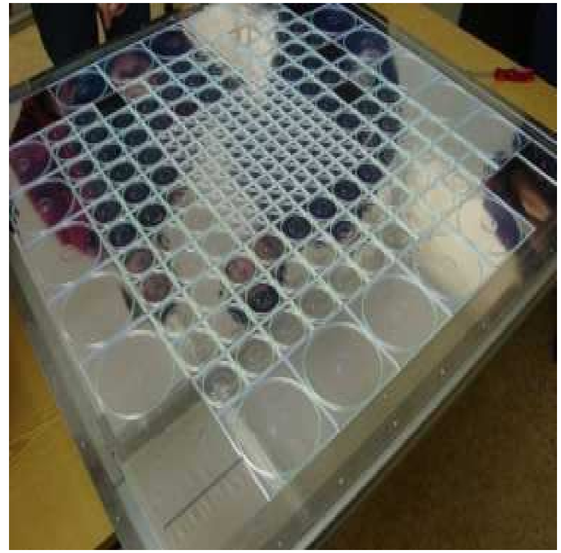
— 1 module: 6x6 1cm^2 pads

— Si PIN diode readout

— total rad. length: 24X_0

— $X_0/\lambda_I = 27.4$

AHCAL



— Tile/steel sandwich struct.

— 38 layers

— 7608 tiles

size: 3x3/6x6/12x12 cm^2

— SiPM readout

— 4.5λ_I interaction length

— prototype setup: 1 m^3

TCMT

— size: 109x109x142 cm^3

— 16 layers

— 1 layer: 8 scintill.strips

— 1 strip: 100x5x0.5 cm^3

— 1 SiPM readout per strip

— 2/10 cm steel absorber

— 5.5λ_I interaction length

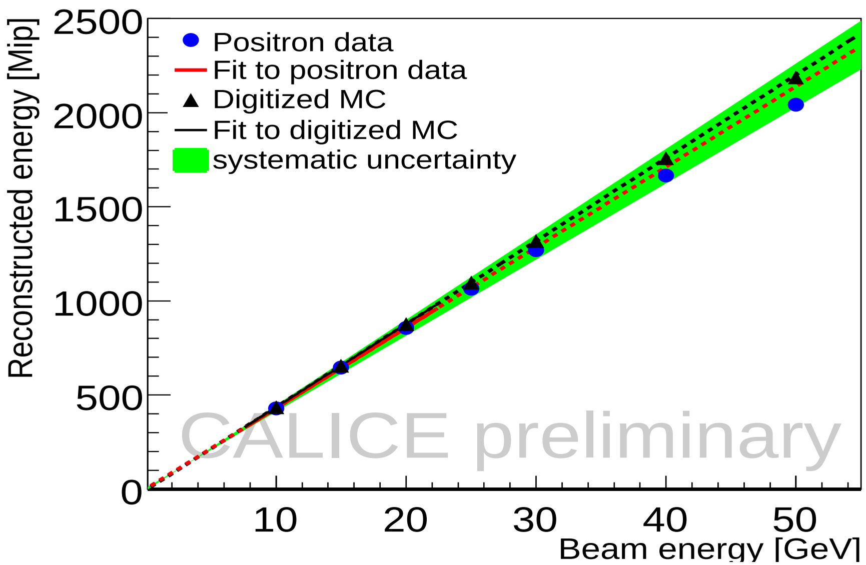
Positron Data Analysis

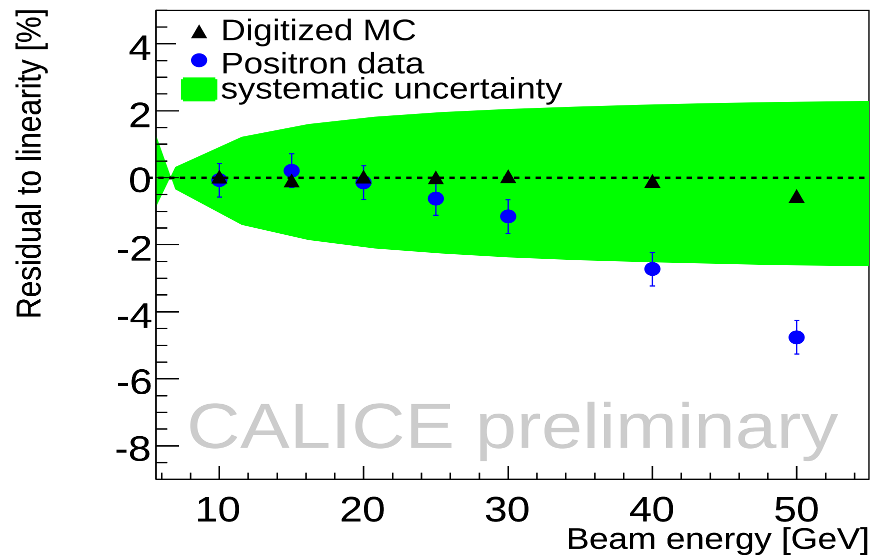
⇒ **Electromagnetic/Muon analysis needed to validate calibration procedure and Monte Carlo digitization**

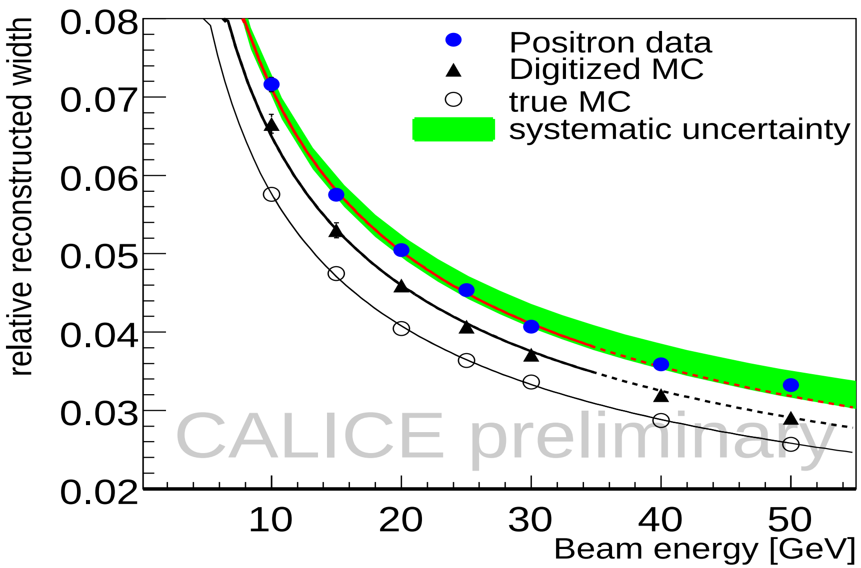
⇒ **Prerequisite to studying hadron showers**

AHCAL Response to Positron Showers

- **Using up-to-date calibrations/corrections to data and up-to-date MC digitization:**







- **Linearity up to 30 GeV**
- **Data stochastic term:**

  $$a = 22.5 \pm 0.1_{stat} \pm 0.4_{syst} [\%/\sqrt{E}]$$

- **Data constant term:**

  $$b = 0 \pm 0.1_{stat} \pm 0.1_{syst} [\%]$$

- **Noise term fixed to 2 MIP**

  $\Rightarrow$ **RMS of pedestal events**

- **Data-MC agreement within 10$\%$**

  Not all calibration uncertainties in MC digitization yet

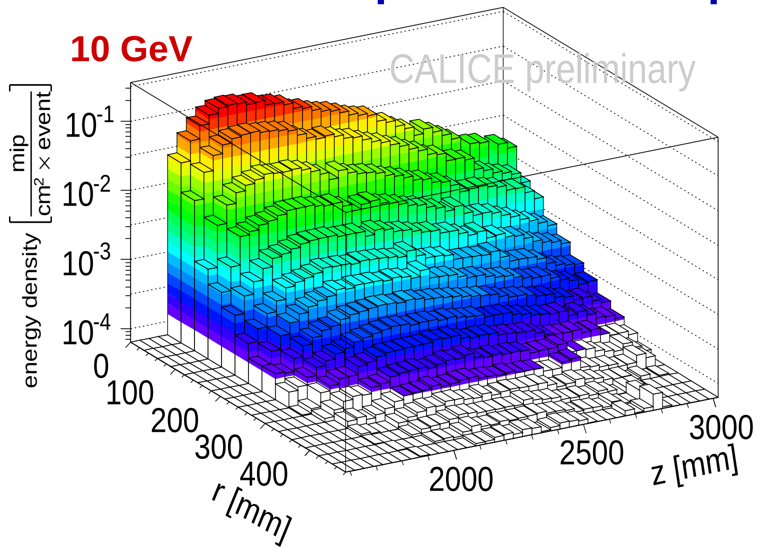
Response to EM showers linear up to tens of GeV

$\Rightarrow$ *enough for hadron analysis*

Pion Data Analysis

Hadronic Showers in AHCAL

- **High granularity of CALICE prototypes allows investigation of longitudinal and lateral shower profiles with unprecedent precision**



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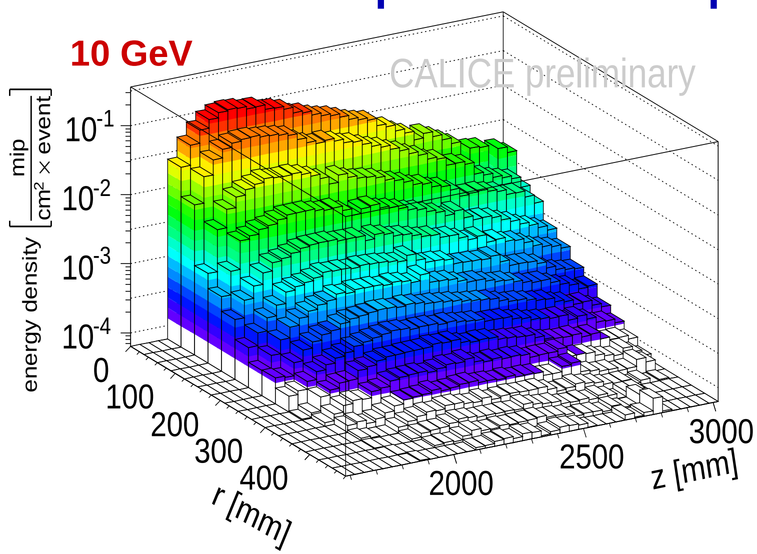
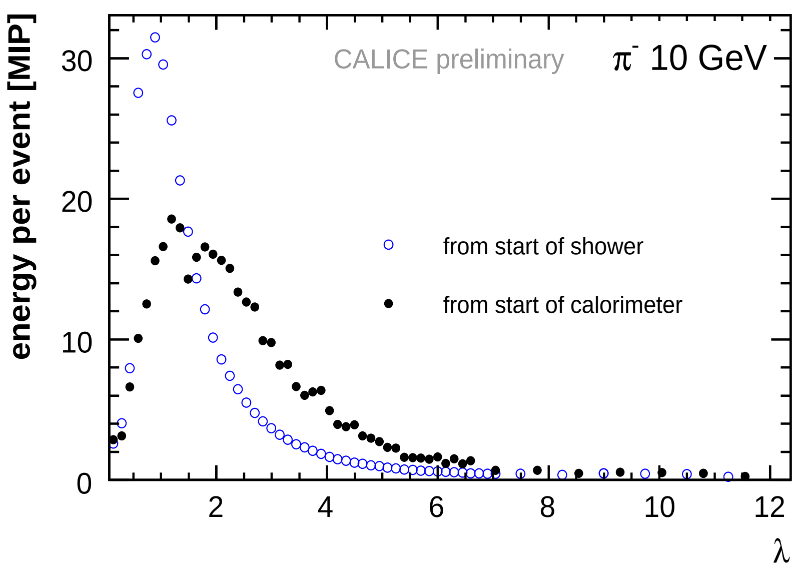
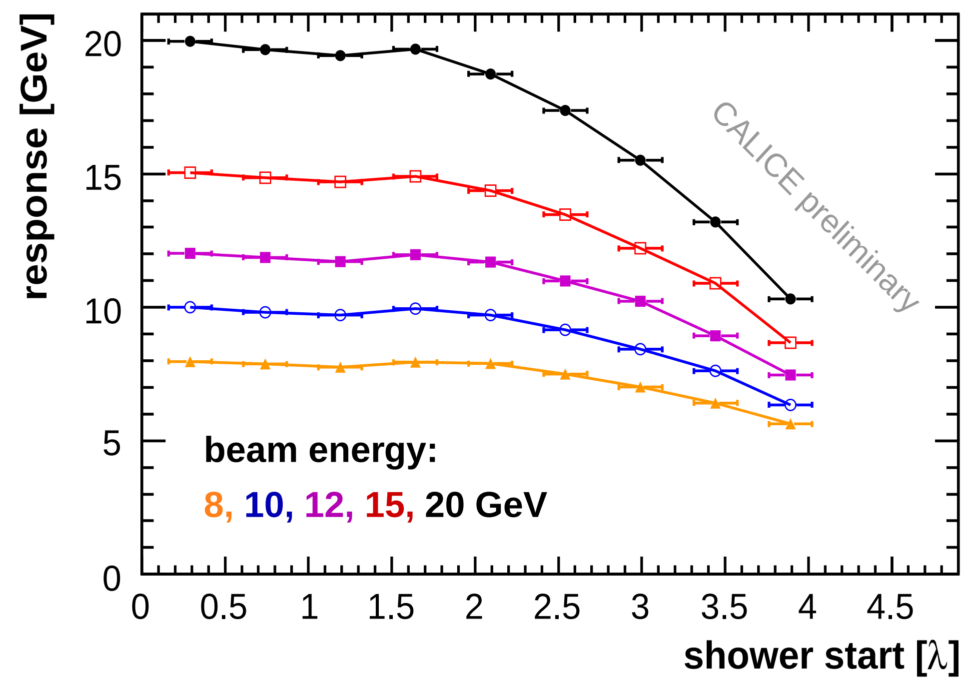


Shower start can be determined

$\Rightarrow$ **taking care of large fluctuations in hadronic shower development**

$\Rightarrow$ **leakage can be measured wrt shower start and corrected for**



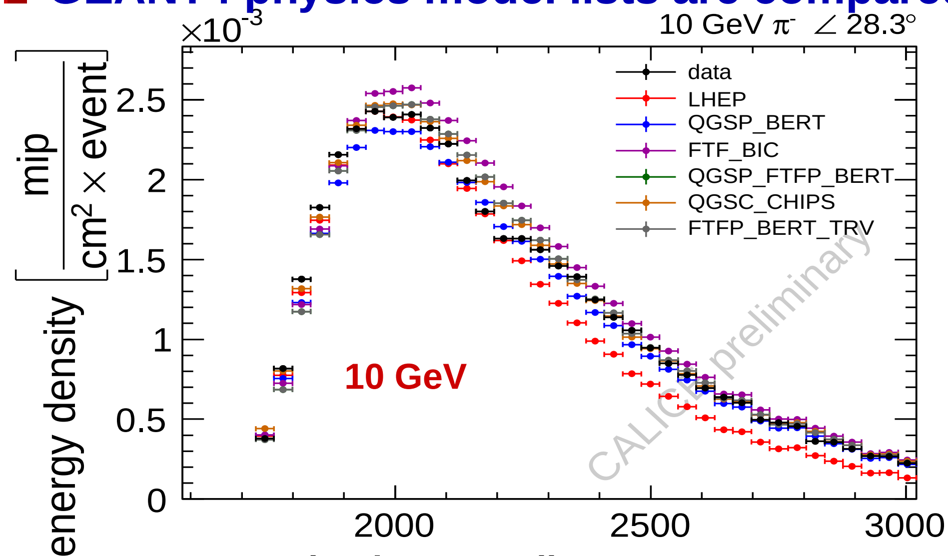


Development of Hadronic Showers

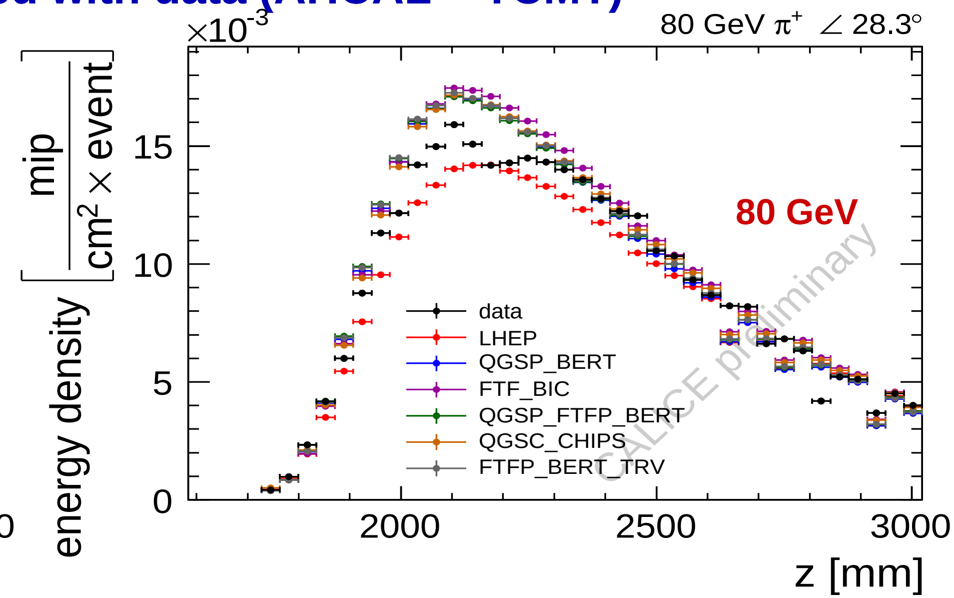
Monte Carlo Comparison with Data [GEANT4 Models]

Longitudinal Hadronic Shower Profiles

- **GEANT4 physics model lists are compared with data (AHCAL + TCMT)**



wrt to absolute coordinates:



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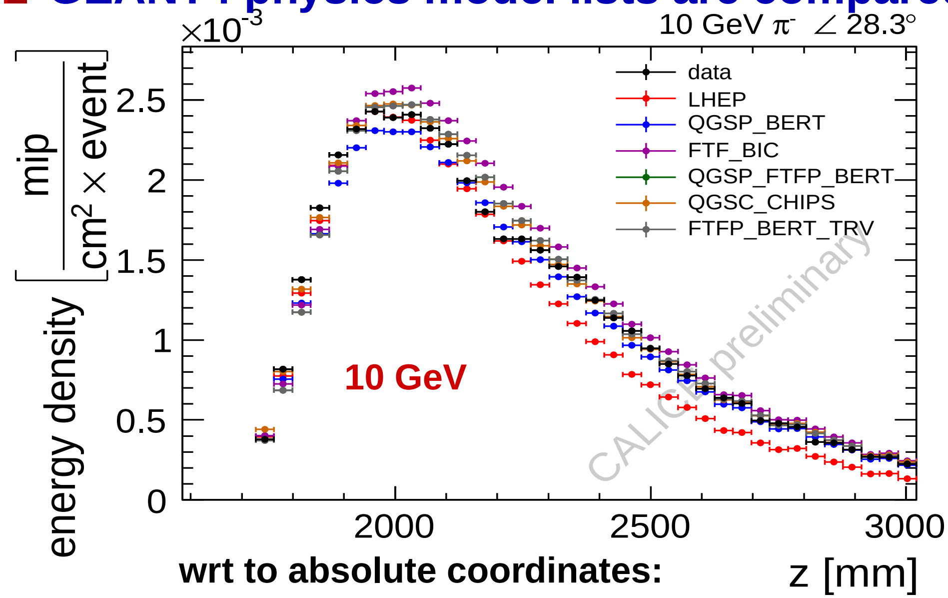

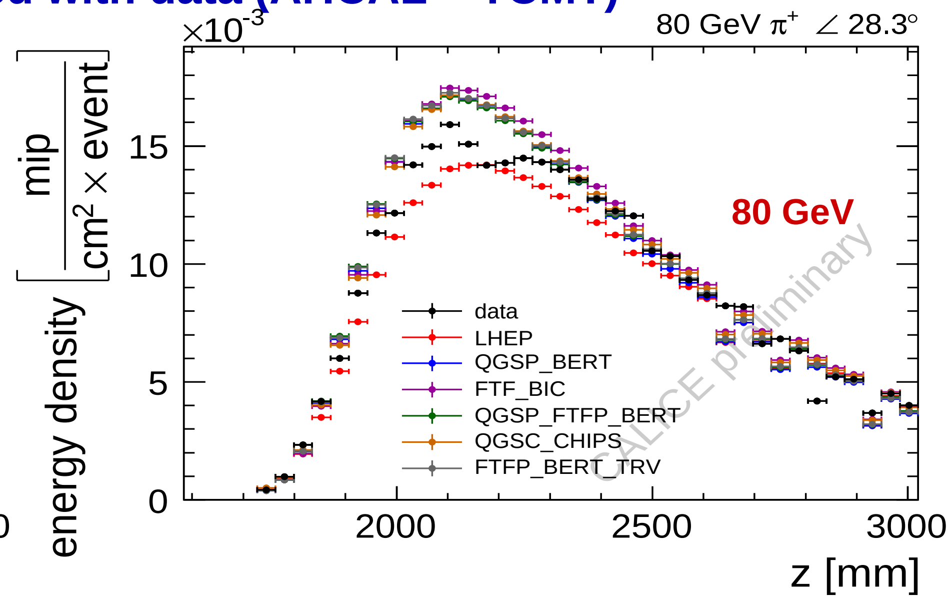

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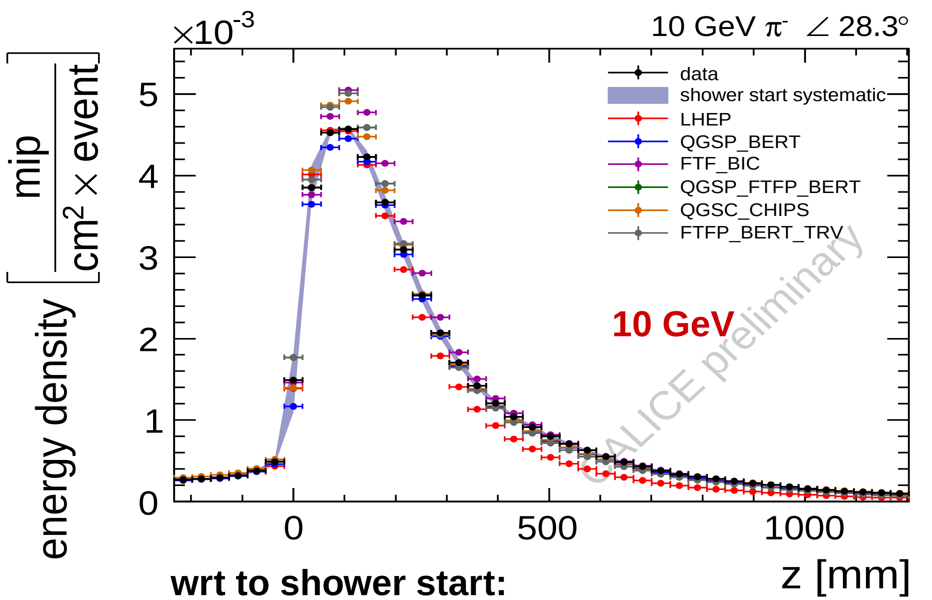

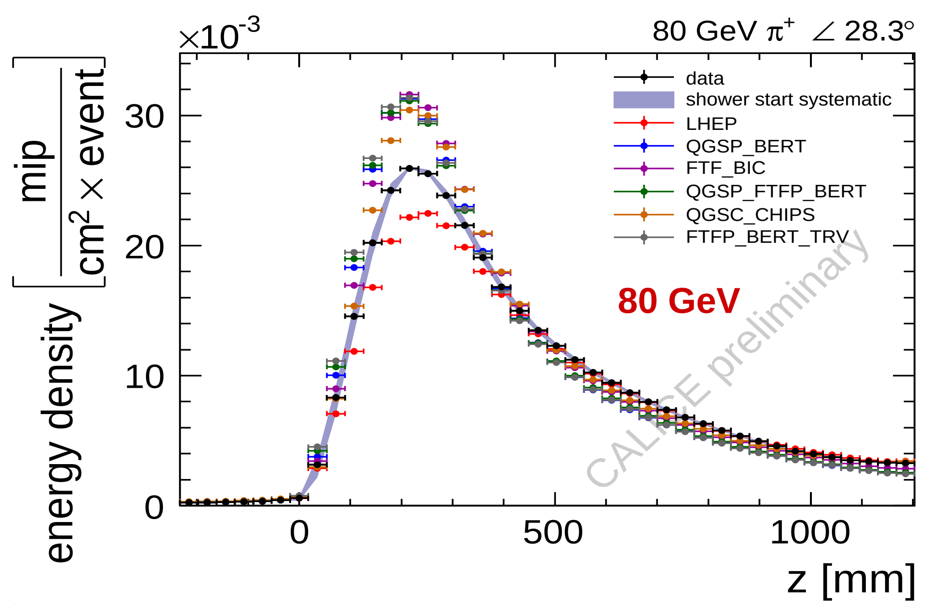

wrt to shower start:

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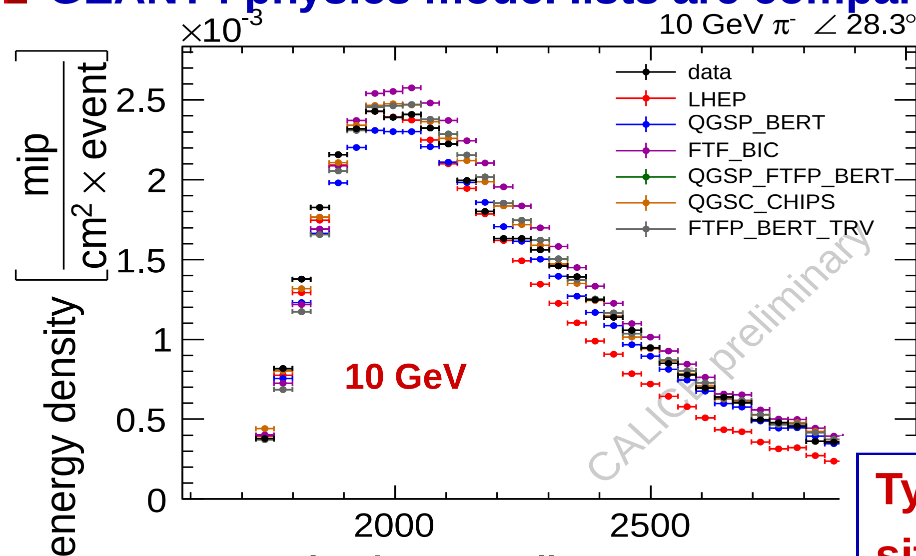
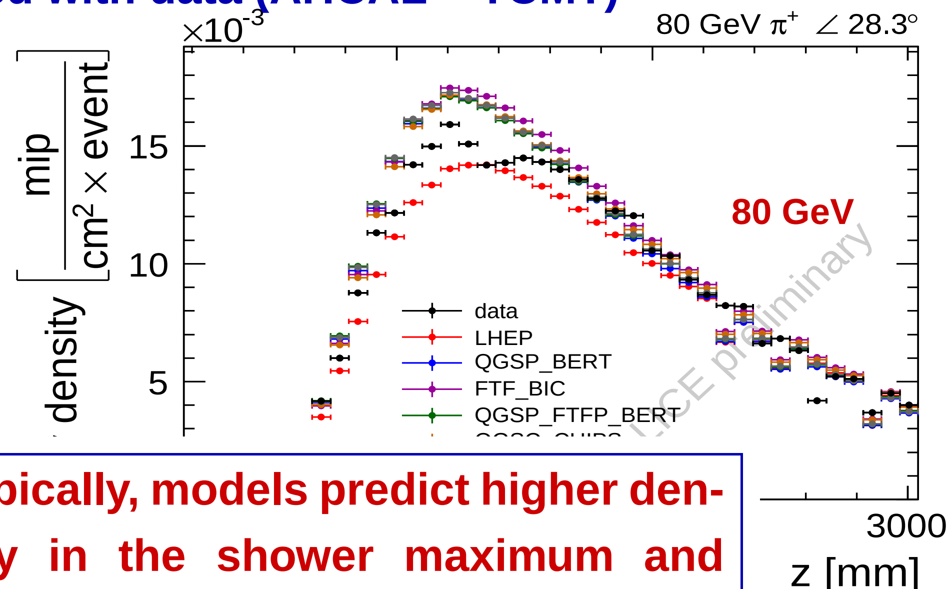
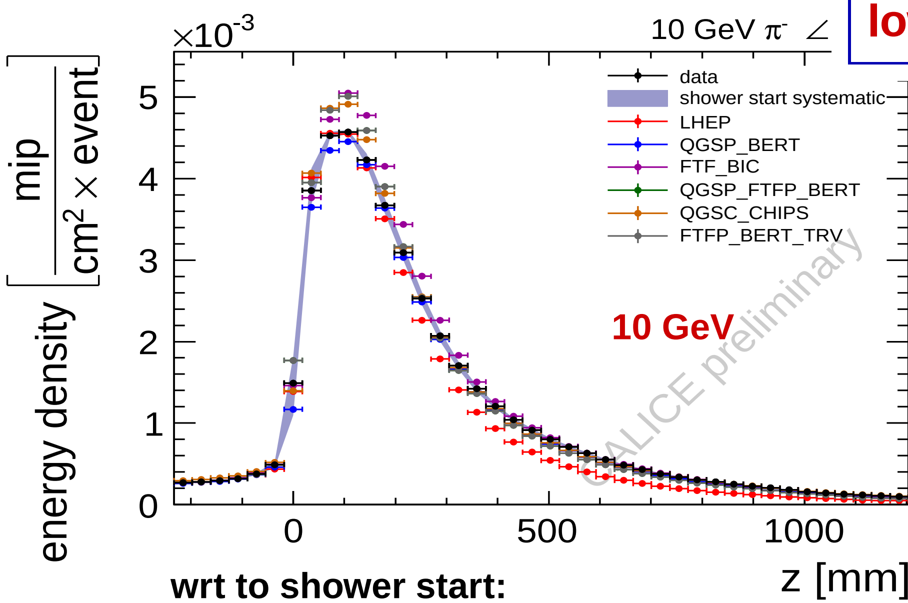




wrt to absolute coordinates:

Typically, models predict higher density in the shower maximum and lower density in the tails



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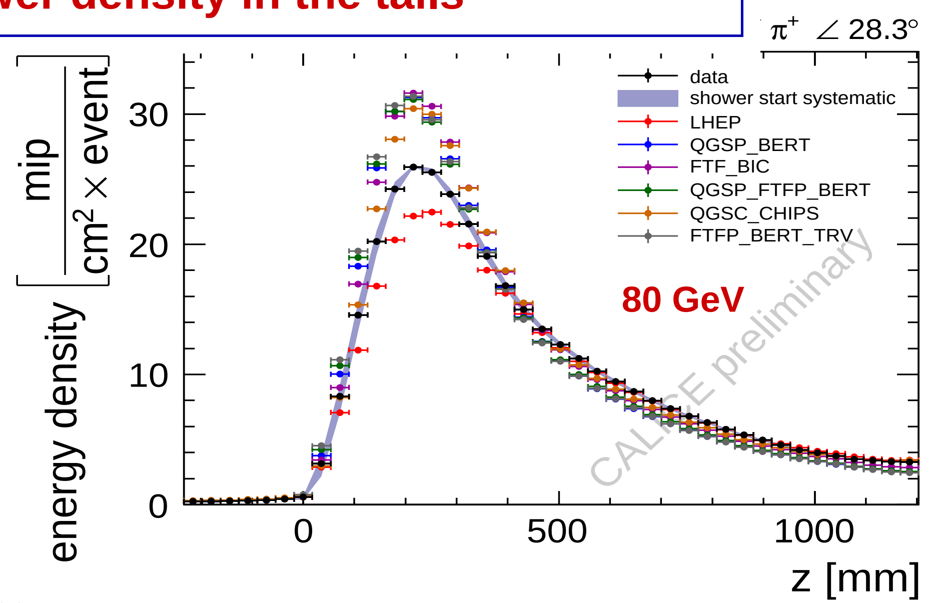
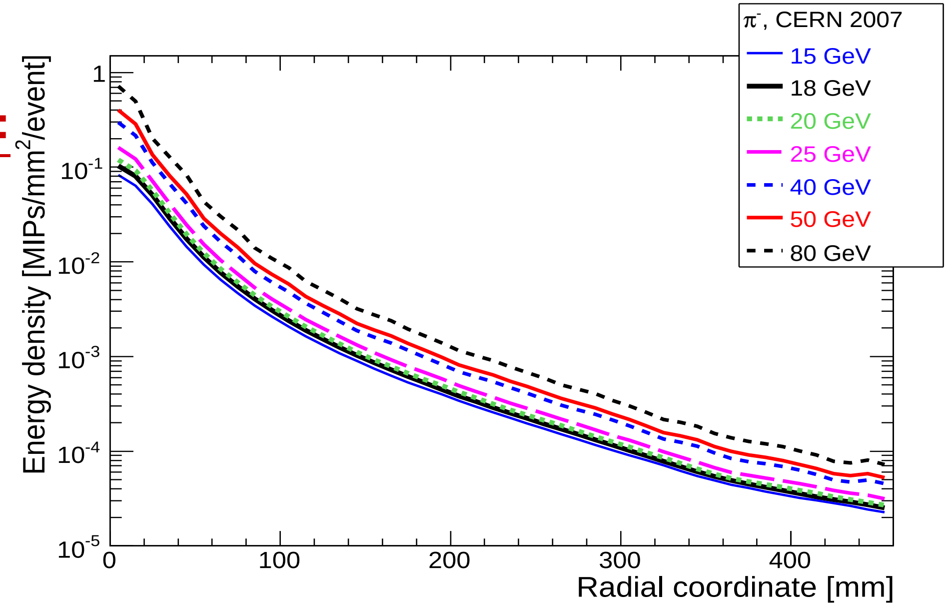


Radial Hadronic Shower Profiles

Measure energy density wrt to primary track:

$\Longrightarrow$ **weak energy dependence**



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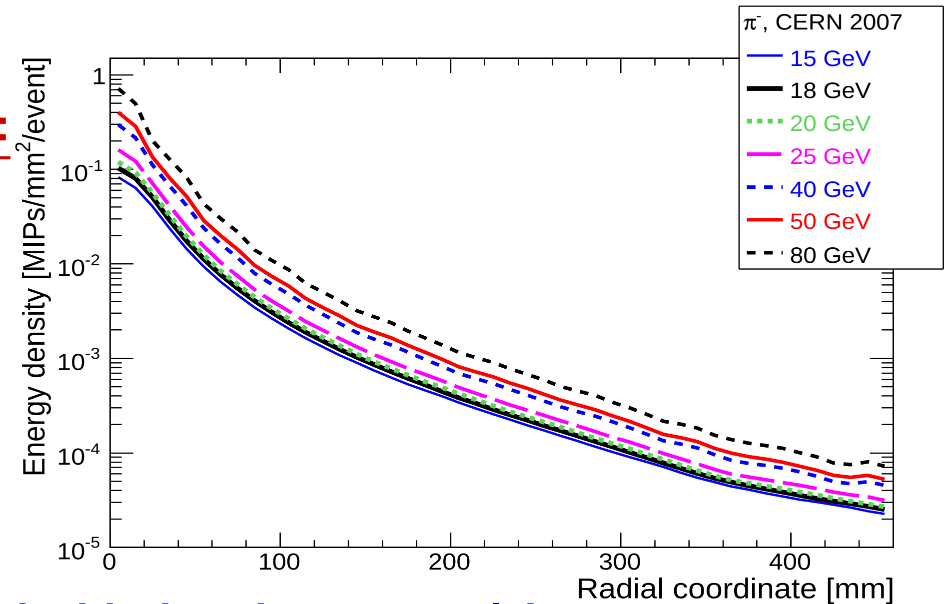
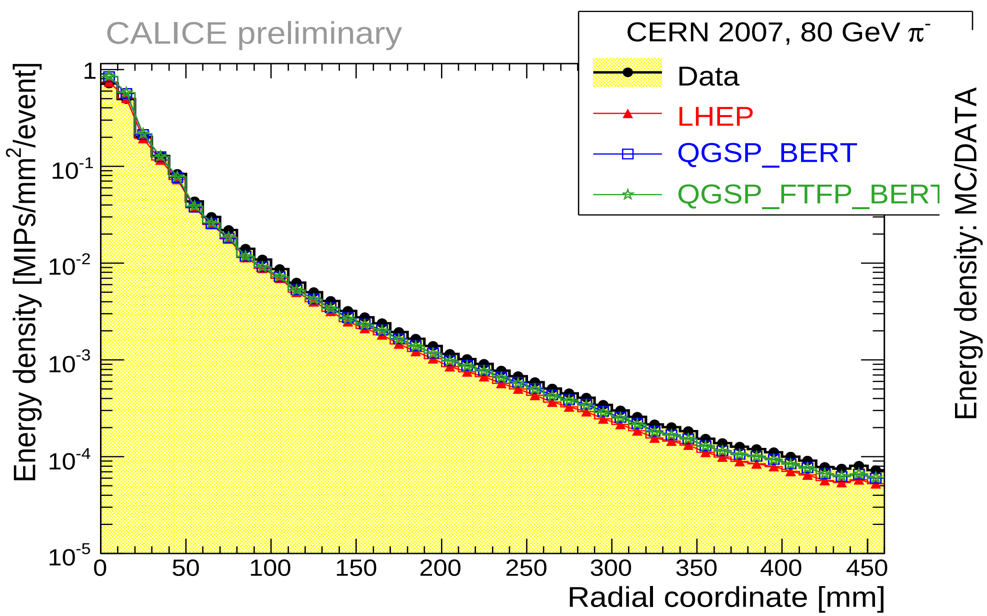
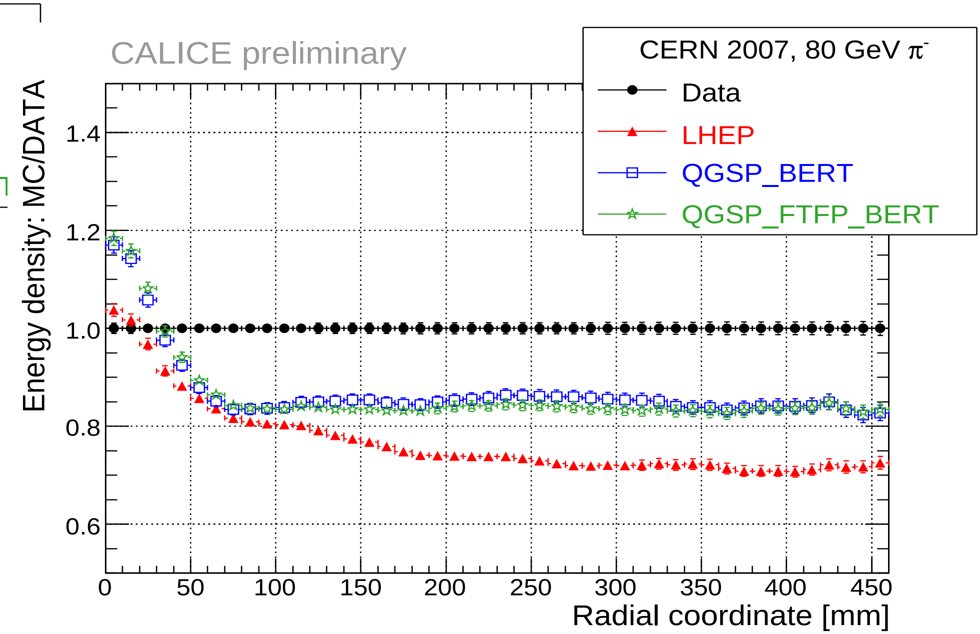


- **GEANT4 physics model lists are compared with data (AHCAL only)**





Radial Hadronic Shower Profiles (continued)

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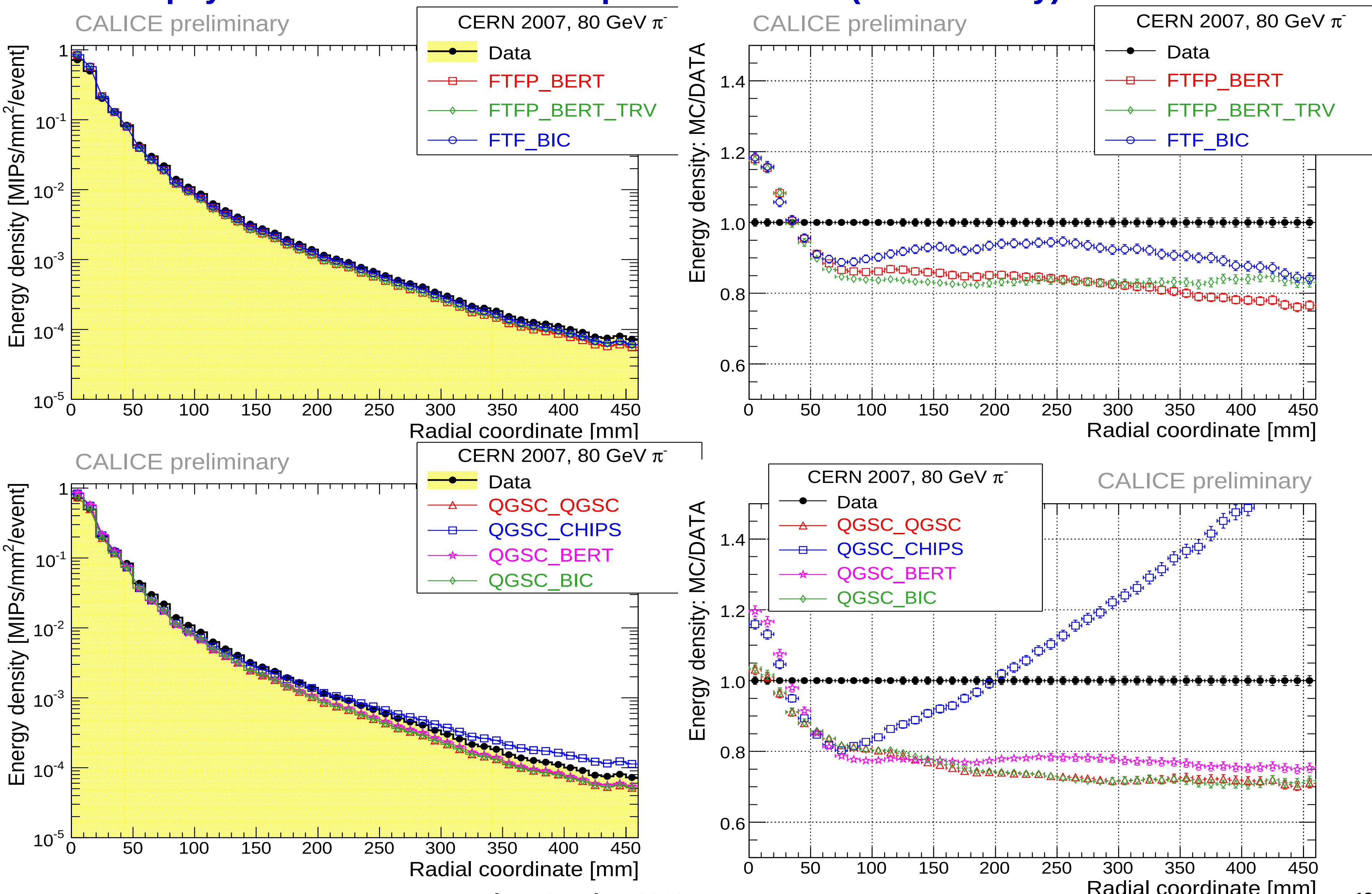

Radial Hadronic Shower Profiles (continued)

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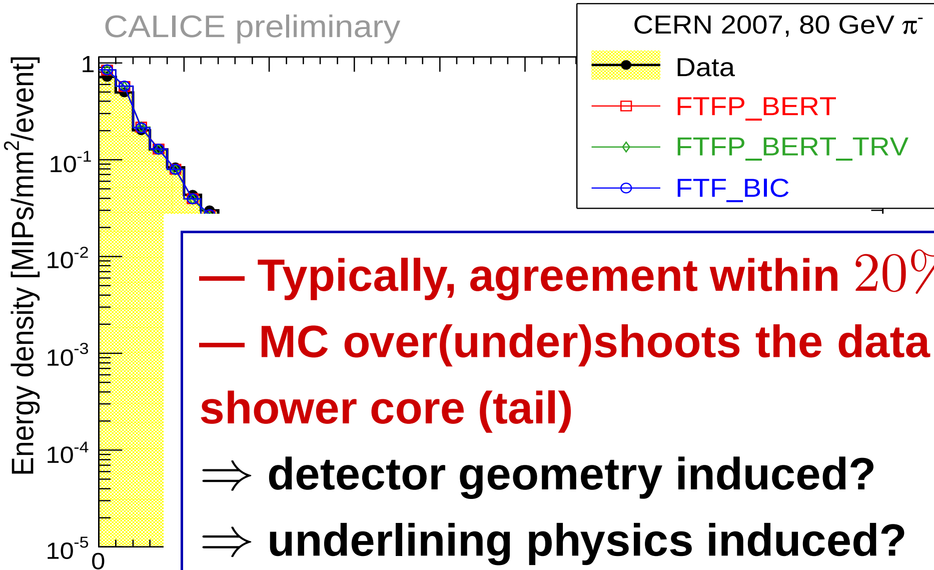
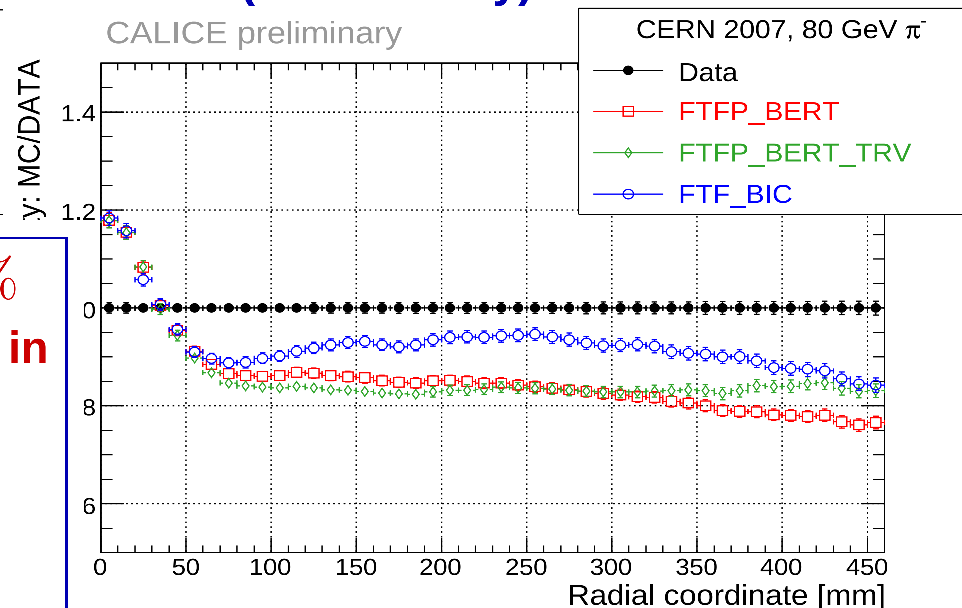




— **Typically, agreement within 20%**

— **MC over(under)shoots the data in shower core (tail)**

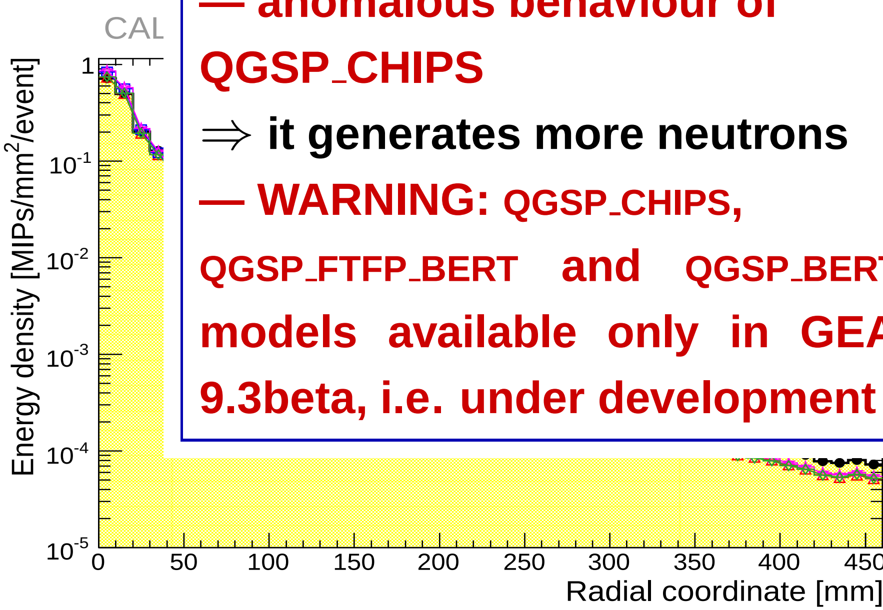
$\Rightarrow$ **detector geometry induced?**

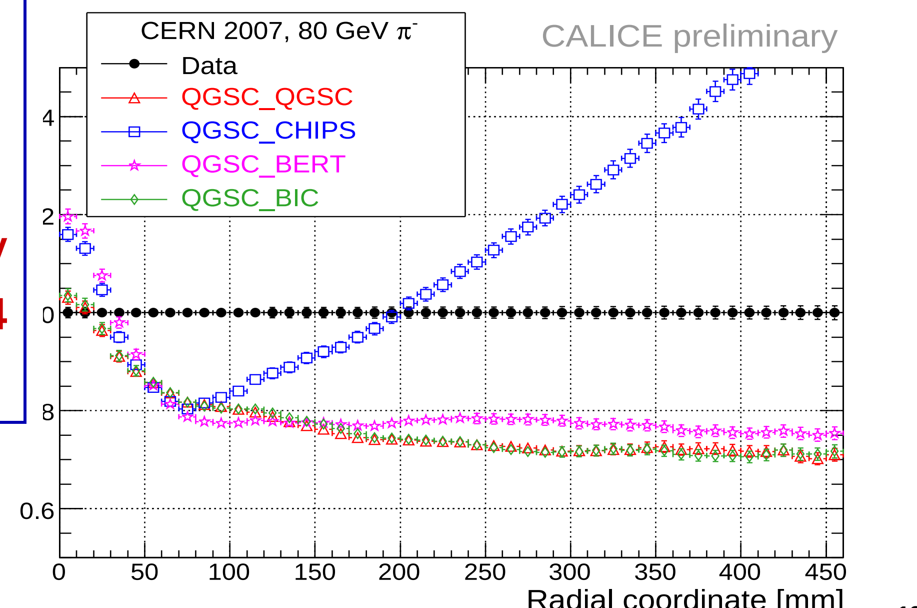
$\Rightarrow$ **underlining physics induced?**

— **anomalous behaviour of QGSP_CHIPS**

$\Rightarrow$ **it generates more neutrons**

— **WARNING: QGSP_CHIPS, QGSP_FTFP_BERT and QGSP_BERT_TRV models available only in GEANT4 9.3beta, i.e. under development**





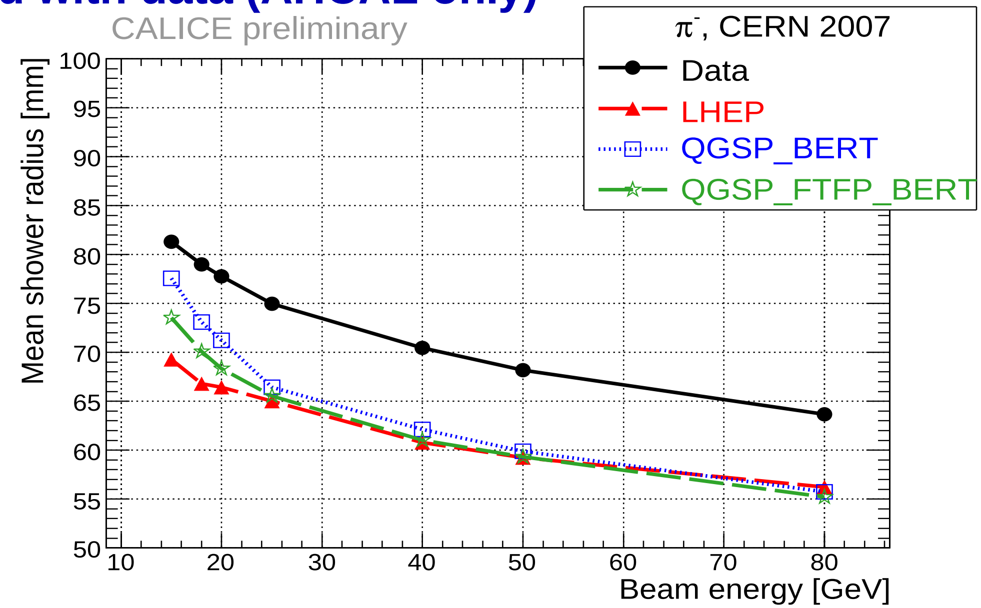
Mean Hadronic Shower Radius

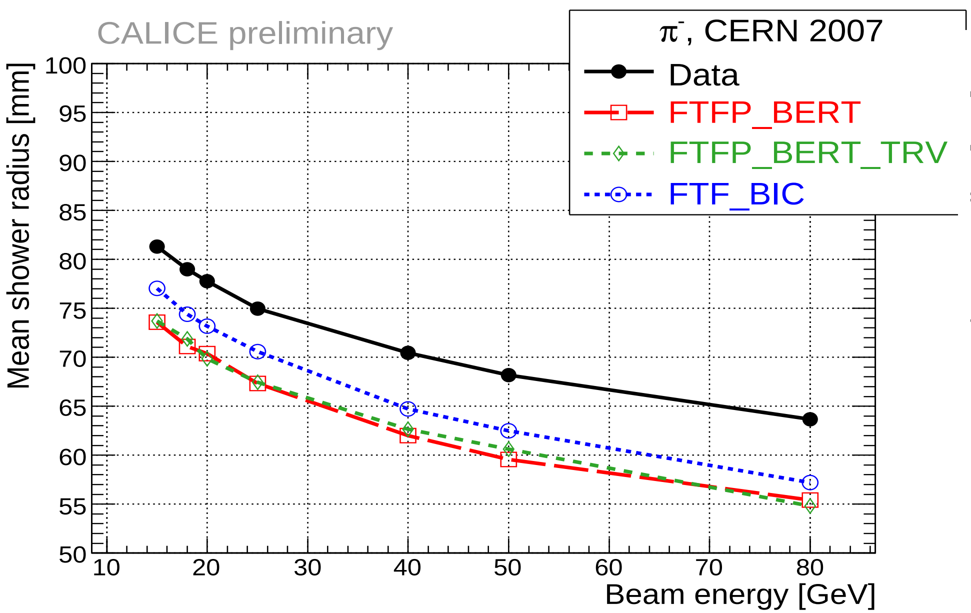
- **GEANT4 physics model lists are compared with data (AHCAL only)**

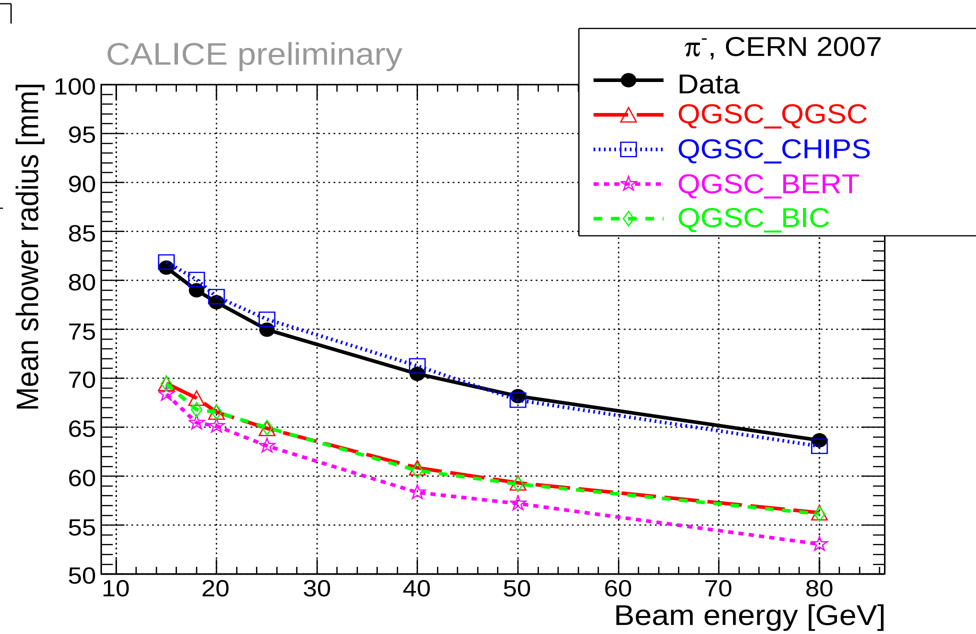
Shower radius for single event:

Energy-weighted mean distance of hits from impinging track

⇒ Mean of shower radius distribution presented here







Mean Hadronic Shower Radius

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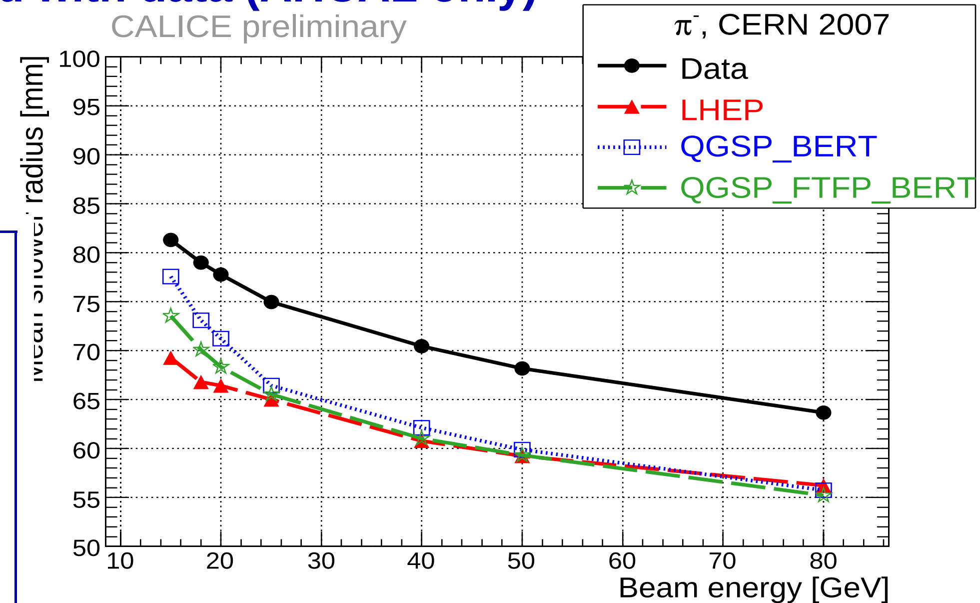
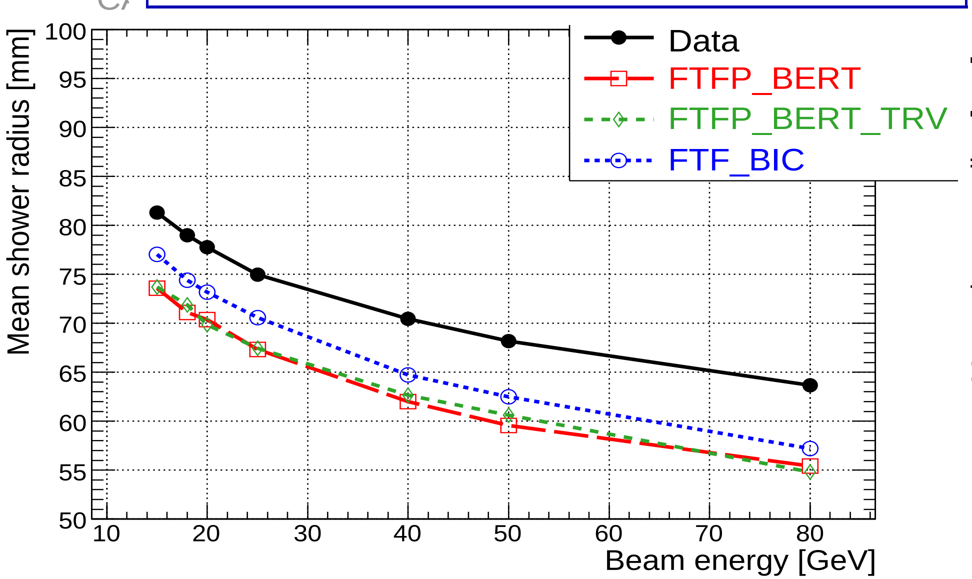
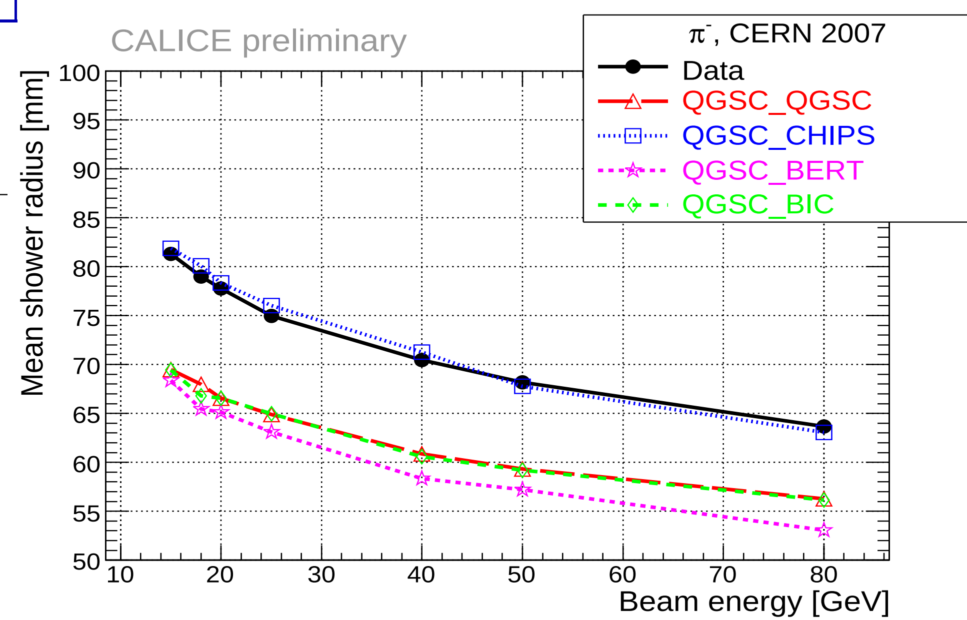


Shower radius for single event:

Energy-weighted mean distance

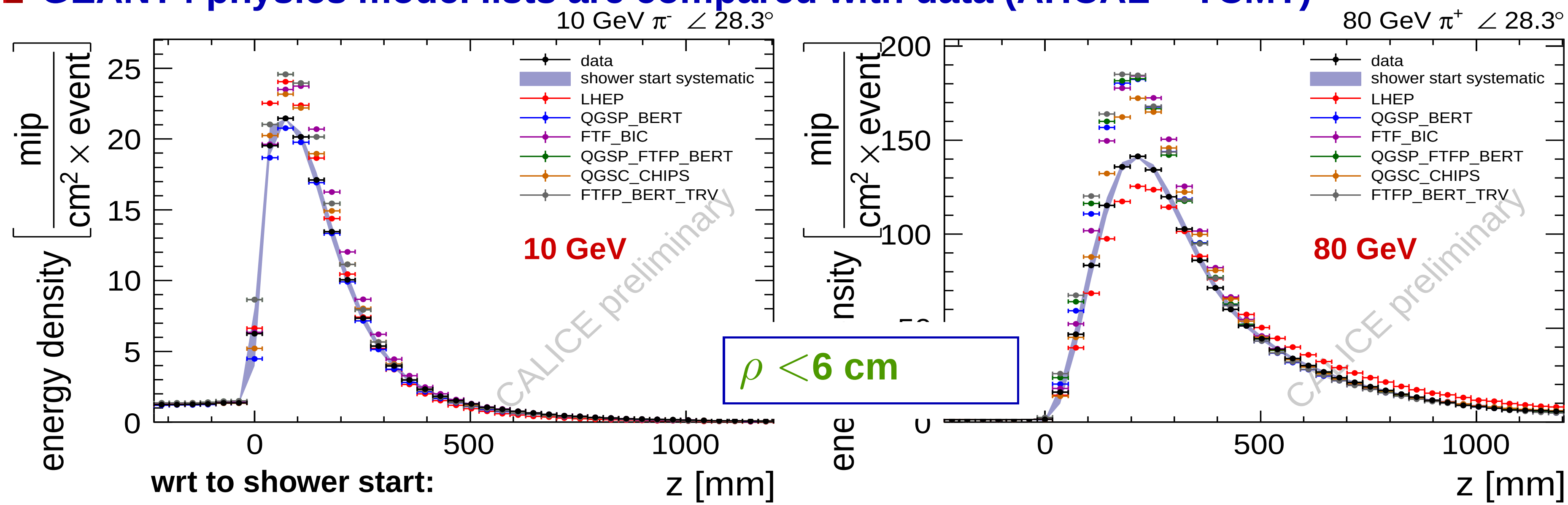
- **Showers become narrower with increasing energy**
- **Predictions typically lower than data**
- **QGSP_CHIPS better matches the data ⇒ contrary to the shape case**





Longitudinal Shower Profiles in Radial Bins

- **GEANT4 physics model lists are compared with data (AHCAL + TCMT)**



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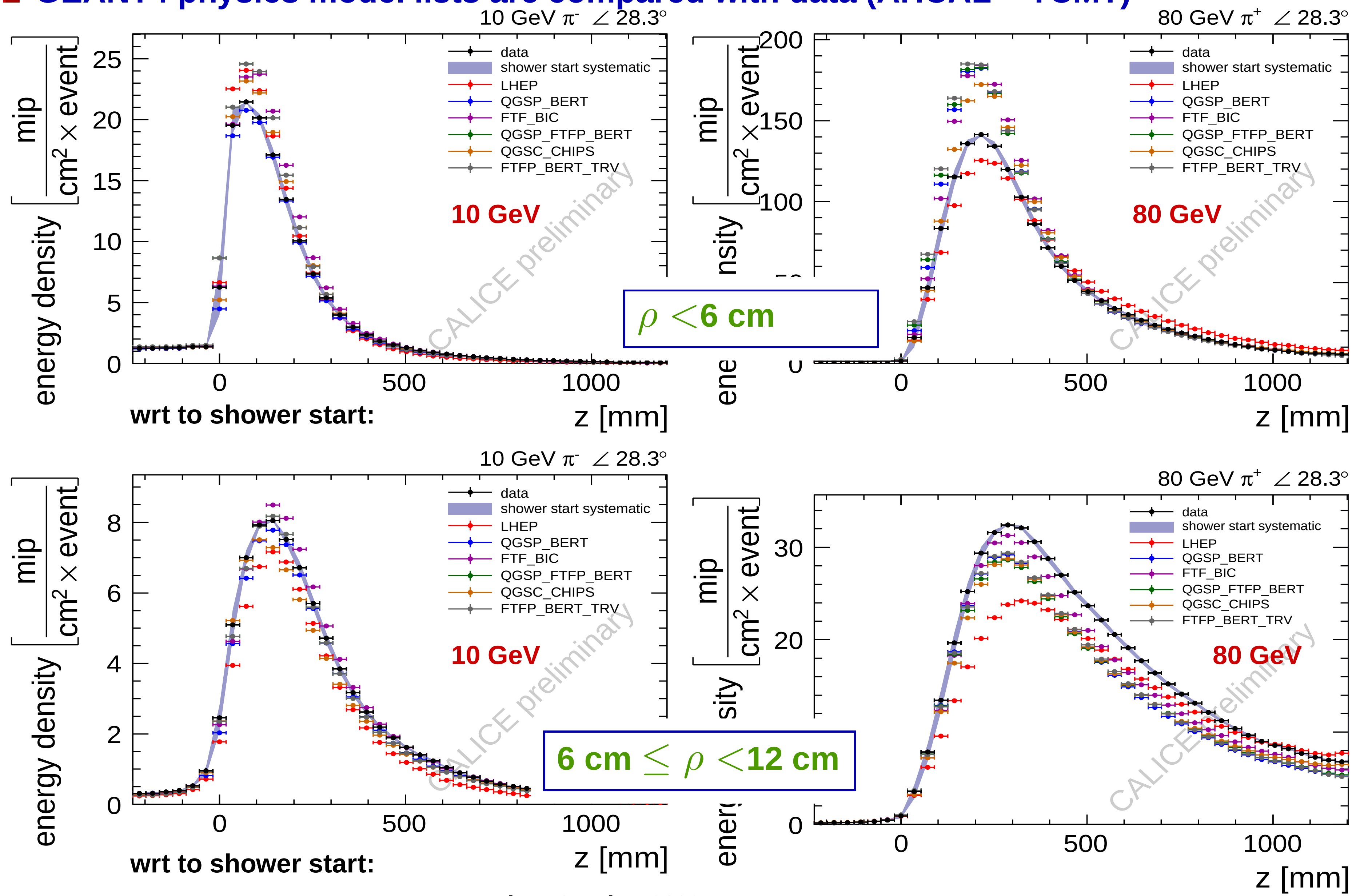

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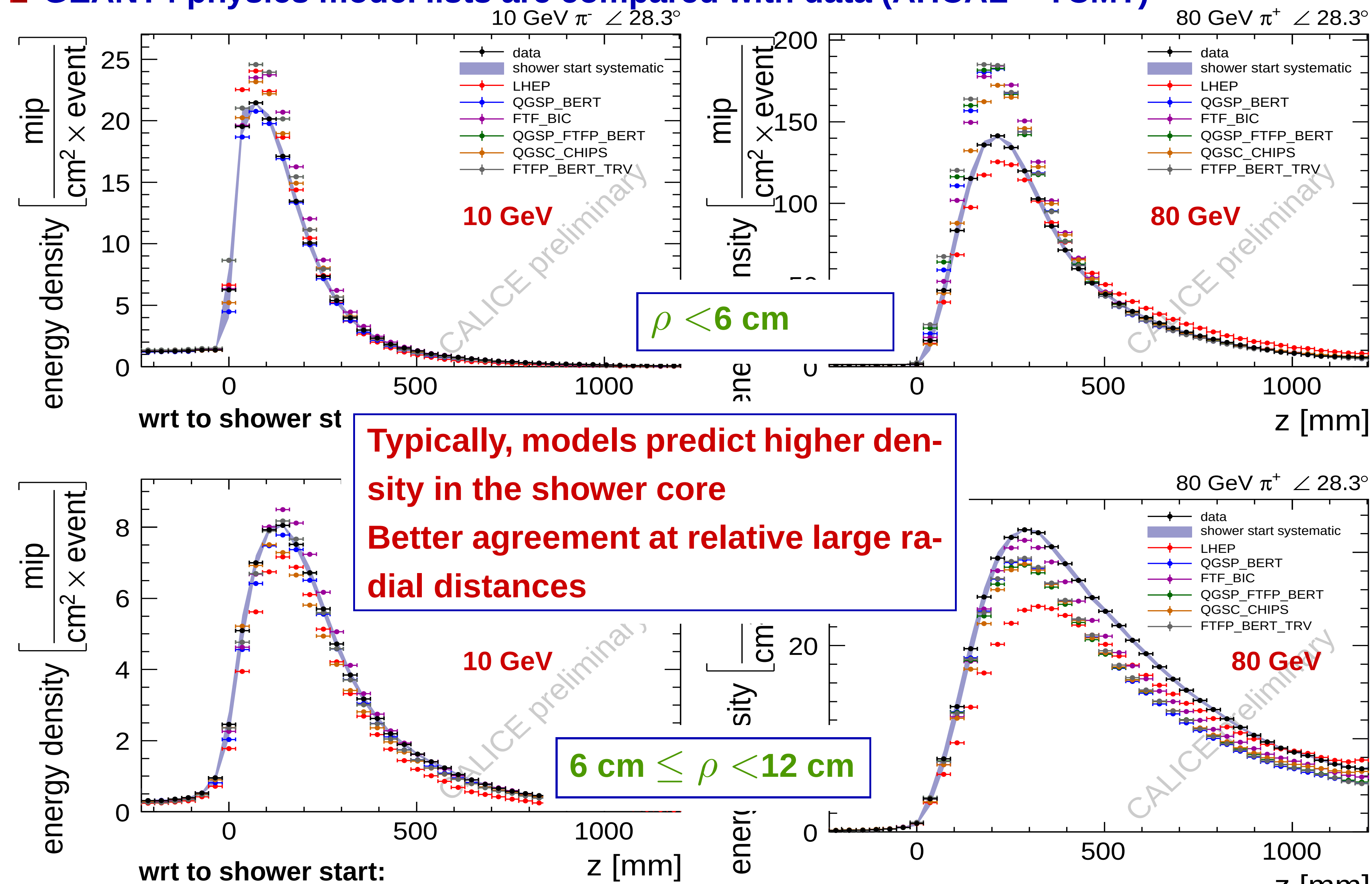

$\rho <$ **6 cm**

Typically, models predict higher density in the shower core

Better agreement at relative large radial distances

6 cm $\leq \rho <$ **12 cm**

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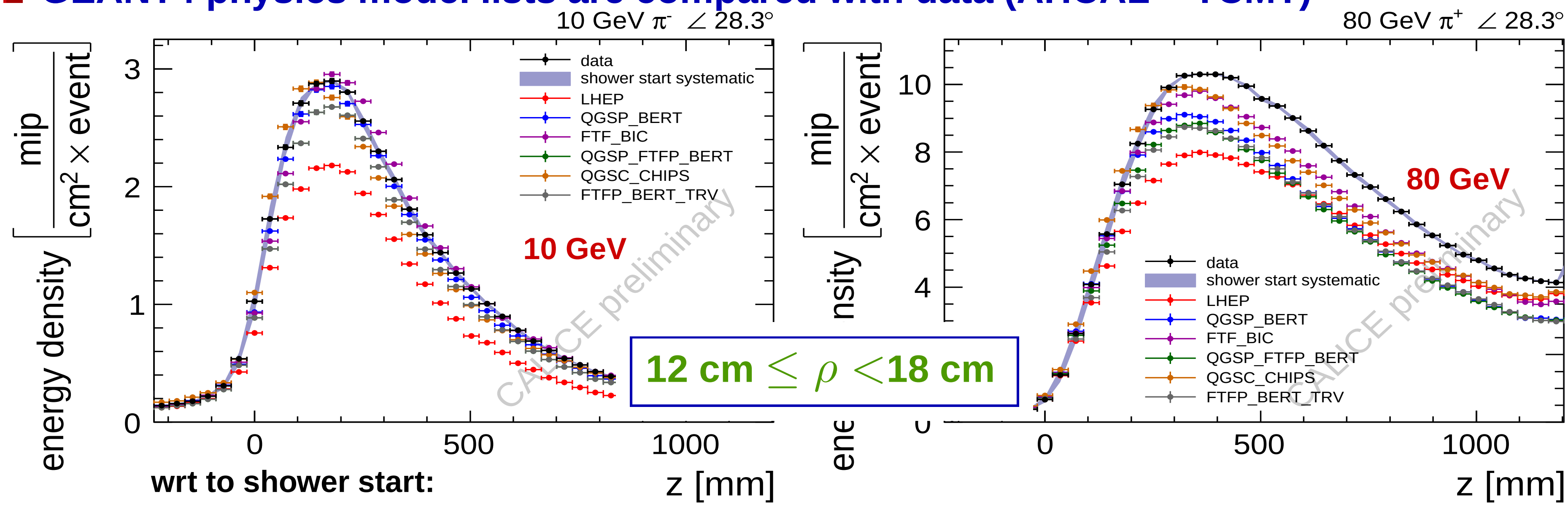

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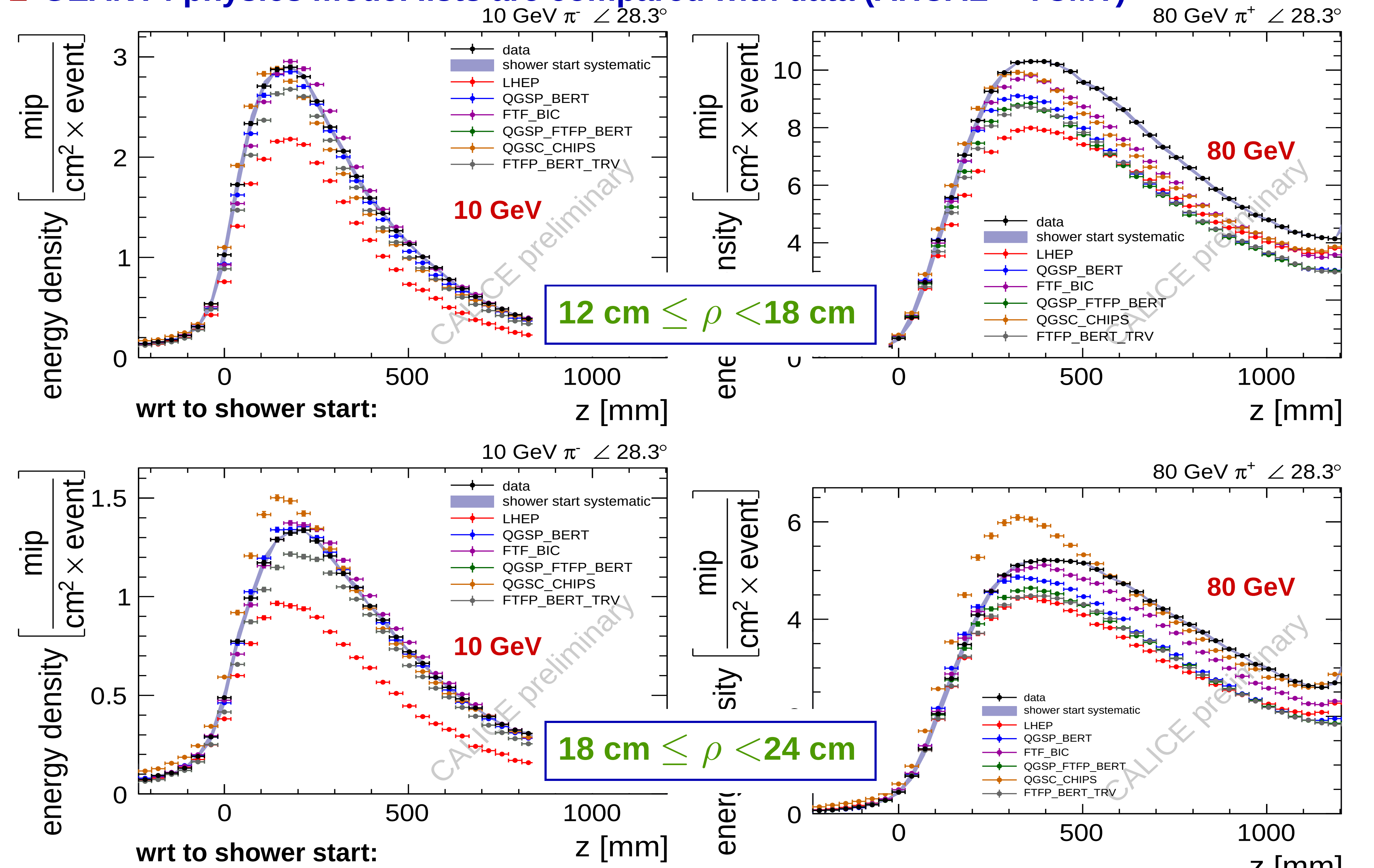

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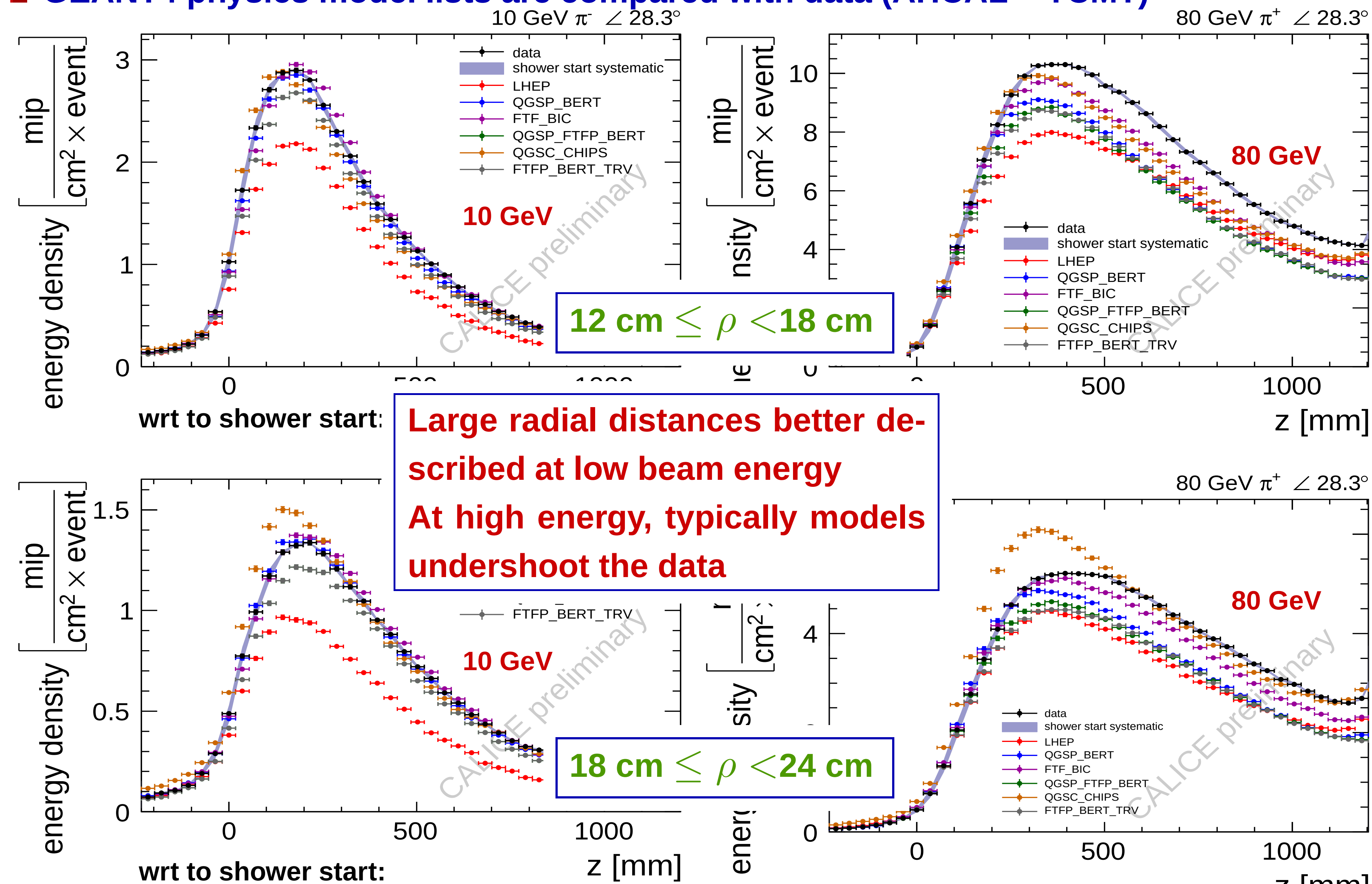


12 cm $\leq \rho <$18 cm

18 cm $\leq \rho <$24 cm

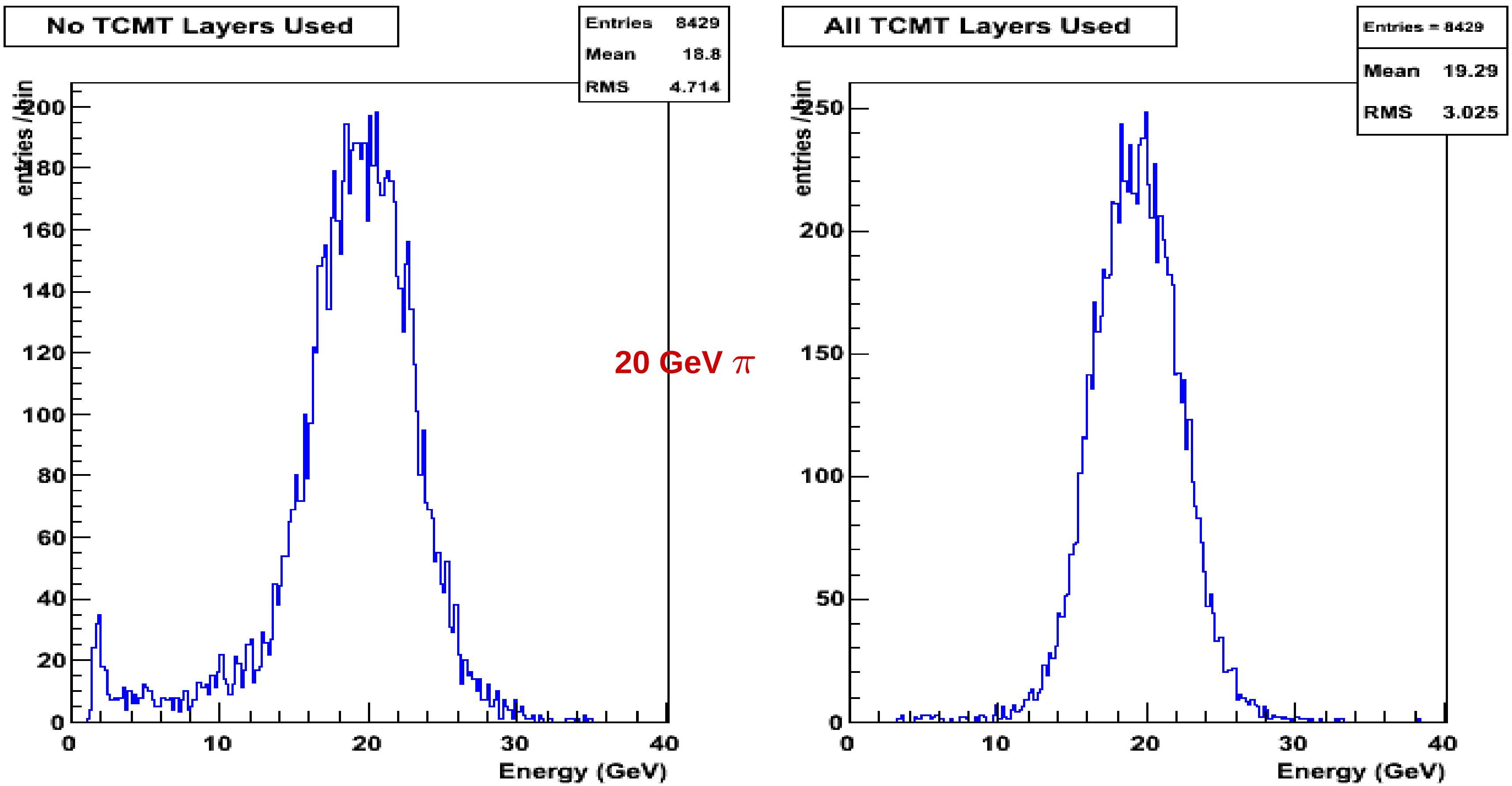
Large radial distances better described at low beam energy

At high energy, typically models undershoot the data

Combining Info from all CALICE Calorimeters

Use of Tail Catcher (TCMT)

- **Tail Catcher ($\approx 5\lambda_I$) needed to contain hadron showers leaking from AHCAL**
- **Used in many analyses presented here**



Energy resolution improves using TCMT

$\Rightarrow$ for showers uncontained in AHCAL

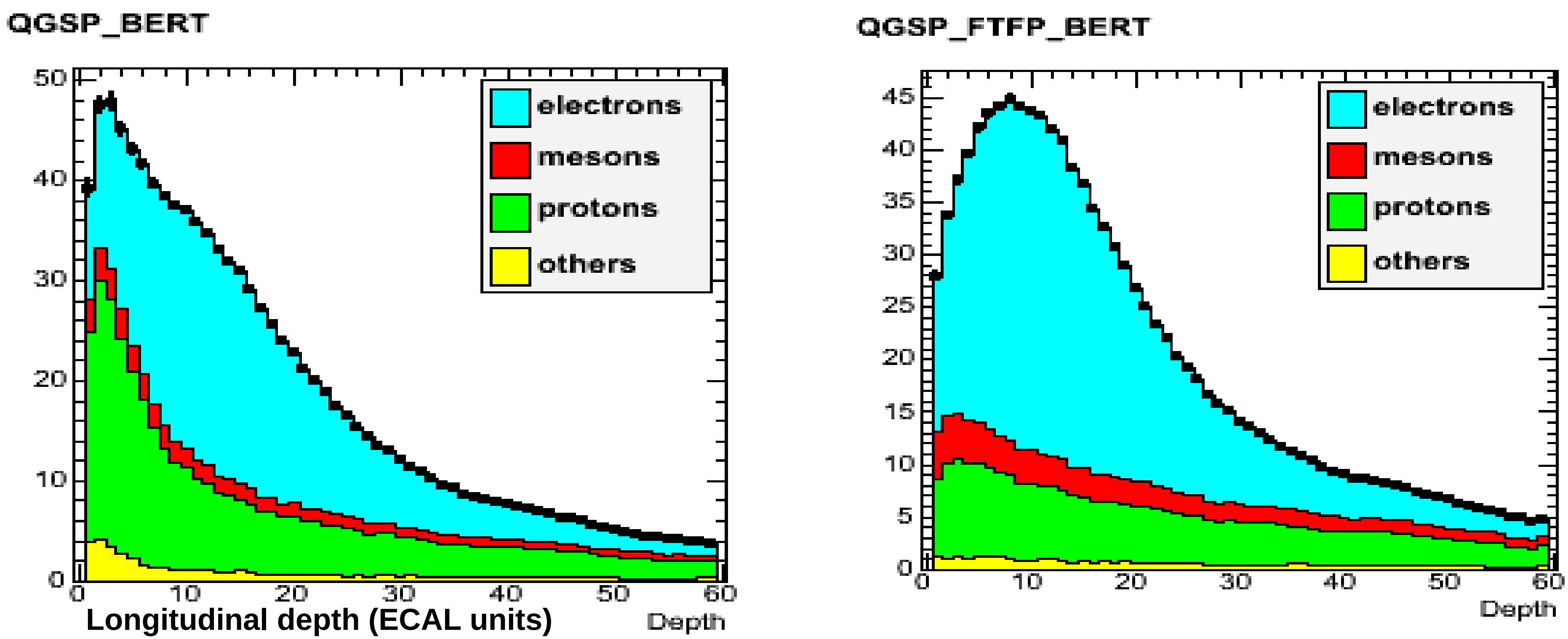
Use of SiW ECAL

- Hadron showers not contained in SiW ECAL ($\approx 1\lambda_I$) $\Rightarrow$ still, many start there
- Calorimeter offers granularity and segmentation higher than AHCAL

  $\Rightarrow$ hadronic shower models have different shapes due different particle components

  $\hookrightarrow$ models can be potentially constrained

Examples of simulations: 8 GeV π^- starting showering at calorimeter start



Analysis with data (not yet released) is ongoing

Summary and Outlook

- CALICE succesfully operated in test beam runs at CERN 2006-07 & FNAL 2008-09

  $\Longrightarrow$ here preliminary results from 2007 data taking period shown

- Detector response to electromagnetic showers understood

  $\Longrightarrow$ linearity within $\approx 4\%$ in electromagnetic analysis

  $\hookrightarrow$ sufficient for hadronic analysis

- analysis on hadronic showers ongoing and developing

  $\Longrightarrow$ Analysis algorithms developed (shower starts, clustering, ...)

- Unprecendented high granularity allows detailed hadron shower investigation

  $\Longrightarrow$ longitudinal/transverse/differential shower development

- Comparison of several models with data

  $\hookrightarrow$ possibly providing constraints on Monte Carlo models

  $\Longrightarrow$ agreement typically within 20%; spotted discrepancies depending on model, incoming hadron energy, analysed observable

  $\hookrightarrow$ ongoing discussion with GEANT4 experts

  $\hookrightarrow$ ongoing efforts to better understand our data

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- **Stay tuned, more to come from CALICE**

Back Slides

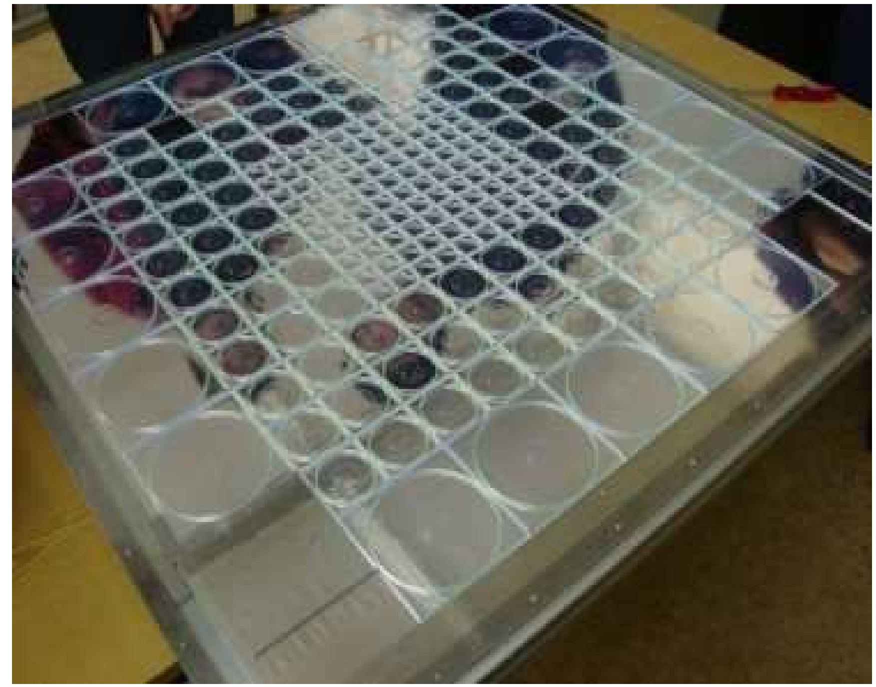
CALICE Test-Beam Detailed Program

- **2006**
  - — DESY: SiW ECAL commissioning
  - — CERN: SiW ECAL, AHCAL, TCMT commissioning
  - — CERN: SiW ECAL, AHCAL(23 layers), TCMT combined physics runs
- **2007**
  - — DESY: W/ScintStrip ECAL commissioning
  - — CERN: W/Si ECAL, AHCAL(38 layers), TCMT combined physics runs
    - $\Rightarrow$ inclined beam incident / calo scan
  - — FNAL: DHCAL test
- **2008**
  - — FNAL: W/Si ECAL, AHCAL, TCMT combined physics runs
    - $\Rightarrow$ inclined beam incident / calo scan
    - $\Rightarrow$ energy range extended down to ≈ 2 GeV
  - — FNAL: W/ScintStrip ECAL, AHCAL, TCMT combined physics runs
- **2009**
  - — FNAL: W/ScintStrip ECAL, AHCAL, TCMT combined physics runs
- **2010 (planned)**
  - — FNAL: SiW ECAL, DHCAL, TCMT combined physics runs

The Scintillator HCAL Prototype

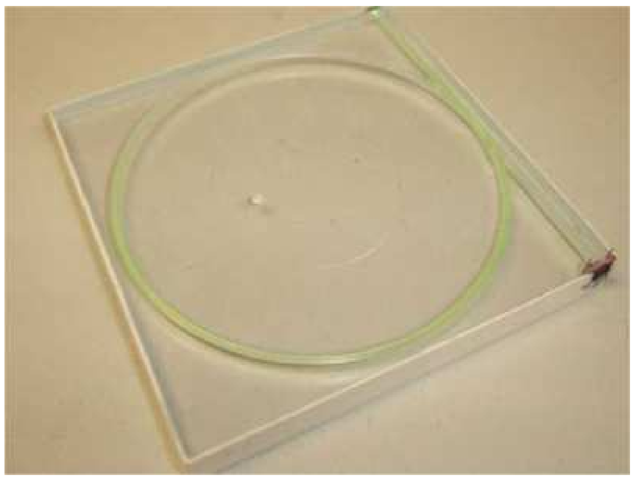
Prototype setup [1 m^3]:

- **38 layers in sandwich structure:**
  - — scintillator tiles + 2 cm absorber (steel)
  - — total interaction length 4.5 λ
- **Tile size: 3x3 cm^2, 6x6 cm^2, 12x12 cm^2**

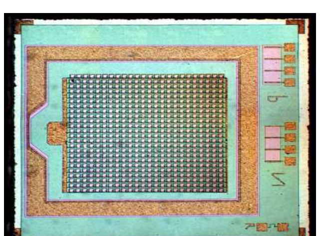


Tot nr. of tiles:

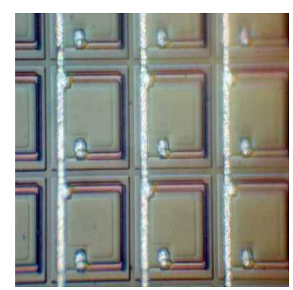
7608



- **One SiPM (1x1 mm^2) per tile:**
  - — wavelength-shifter coupled
  - — developed by MEPhi/Pulsar

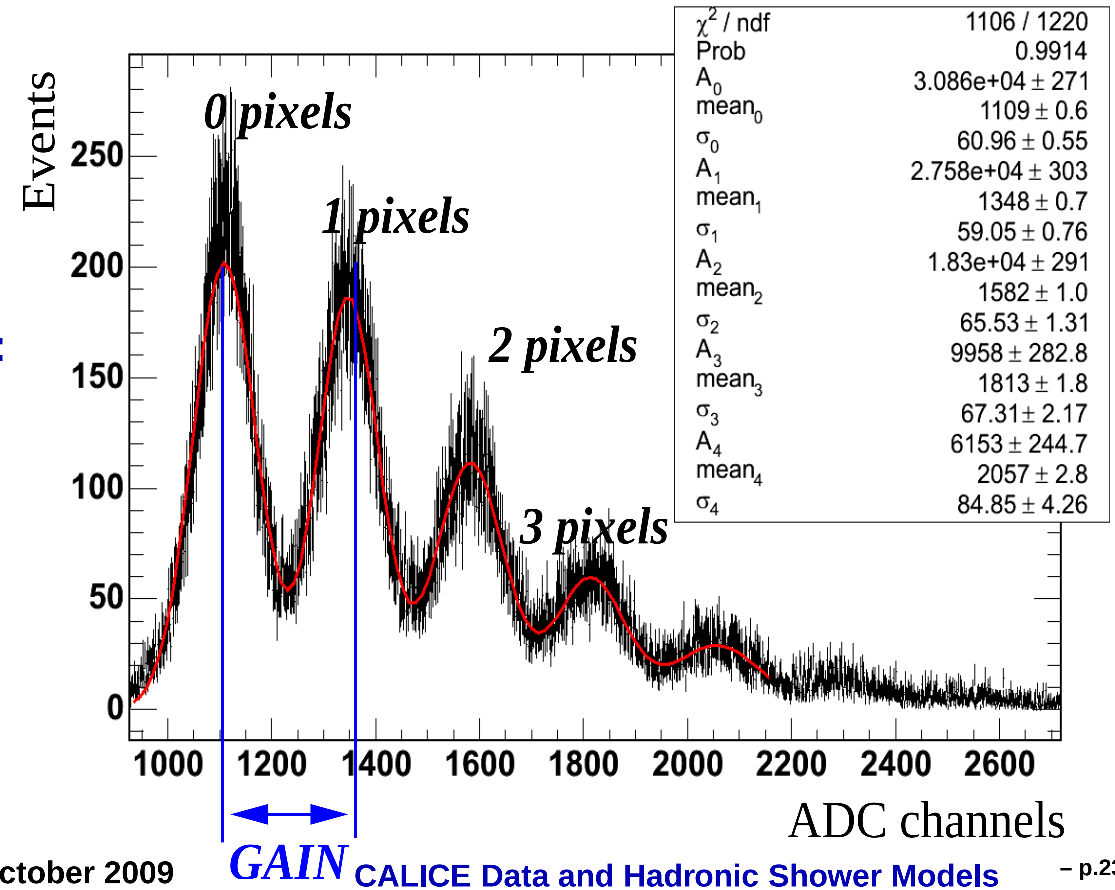


- **1156 pixels (30x30 μm^2) per SiPM:**
  - — Geiger mode



Gain Calibration

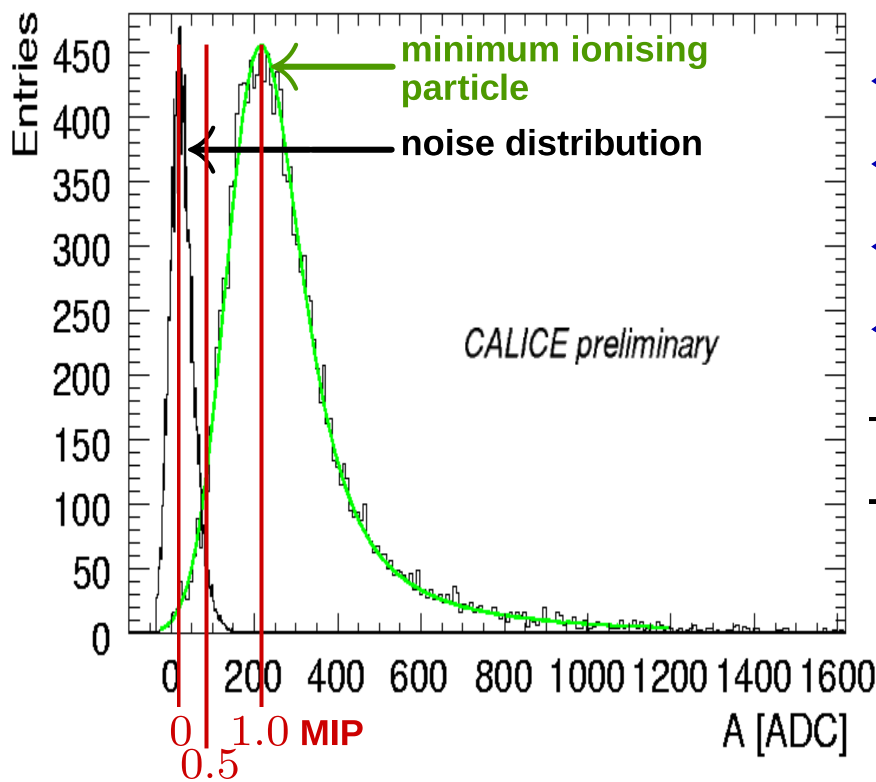
- **Gain defined as $G = \frac{Q_{pixel}}{e}$: $\Longrightarrow$ typically $Q_{pixel} \approx$ a few 100 fC $\approx 10^6$ e**
- **Each SiPM has its own gain**
- **Gain can be monitored via dedicated measurements during data taking**
  - **— illuminate SiPMs with low intensity LED light**
  - **— fit single-pixel spectra for each SiPM**
  - **— gain $\propto$ distance between two adjacent pixel peaks**



- **Calibration efficiency (CERN data):**
  - **— 96.9% SiPMs calibrated**
  - **— 1.7% LEDs off**
  - **— 1.4% missing calibration**

MIP Calibration

- **MIP calibration: conversion from Hw ADC values (variable from channel to channel) to a physical quantity**
  - $\Rightarrow$ **SiPM response to passage of minimum ionizing particles**
  - $\Rightarrow$ **calibration done using muon beam at CERN**



For every tile:

- **fit muon signal with Gauss+Landau**
- **set MIP to MPV from fit**
- **from Monte Carlo: 1 MIP = 0.861 MeV**
- **in analysis reject hits below 0.5 MIP**

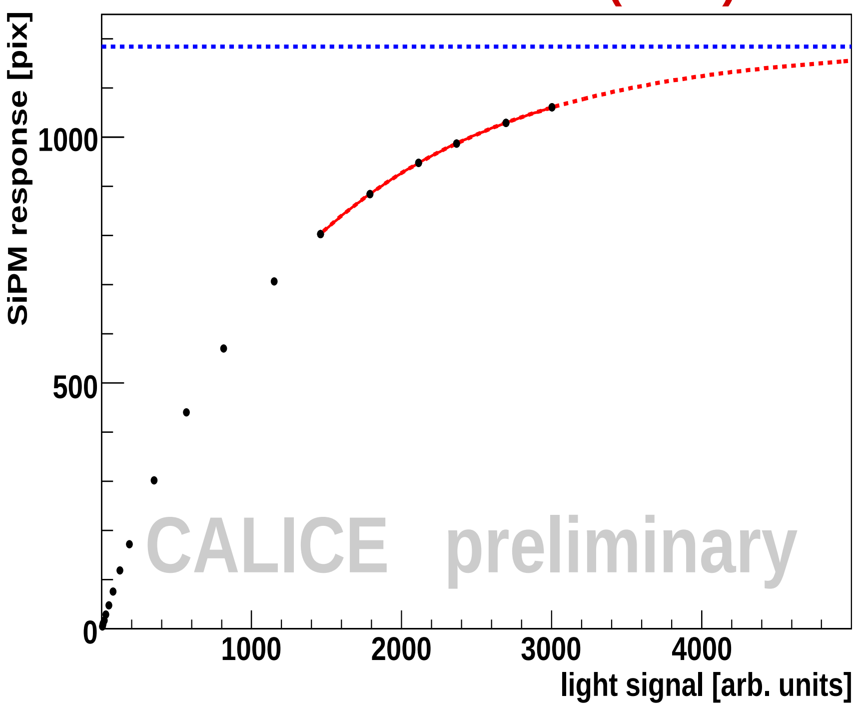
— **mip detection efficiency (A_{mip}/σ_{mip}) $\approx 93\%$**

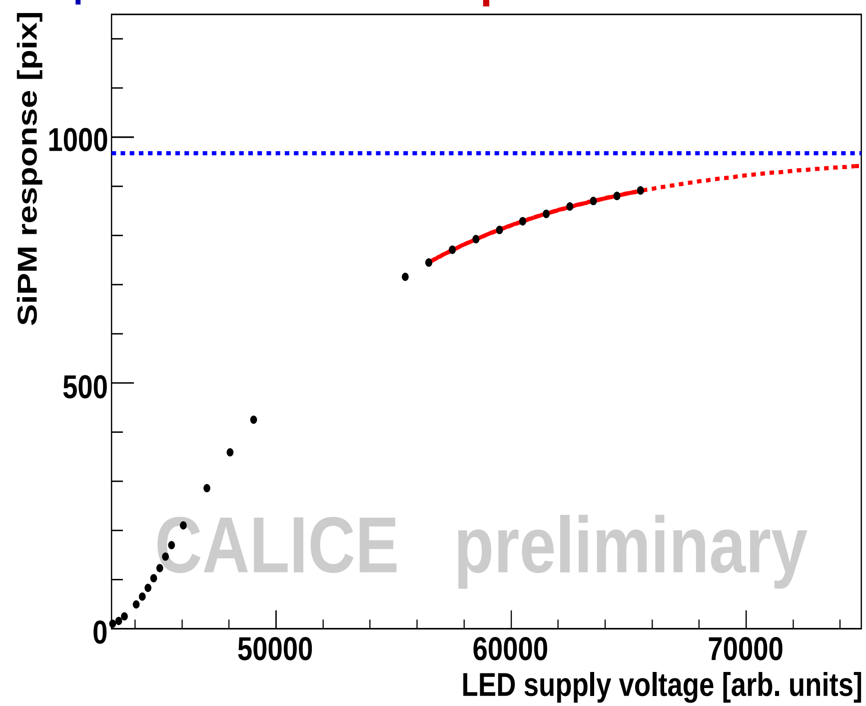
— **MIP scale total uncertainty: $\approx 2\%$**

Saturation Correction

- SiPMs non-linear due to limited number of pixels (1156) and to pixel recovery time
- Non-linearity corrected with saturation curves [response vs input signal]
  - — two sets of curves available: ITEP and LED monitoring system
  - — differences between them originated by fiber-SiPM mis-alignement

test-bench curve (ITEP) One SiPM example: in-situ response curve





- UP to 2007: curves from ITEP
- NOW: extract asymptotic level from in-situ curves and rescale ITEP curves

$\Rightarrow$ improvement in calorimeter response

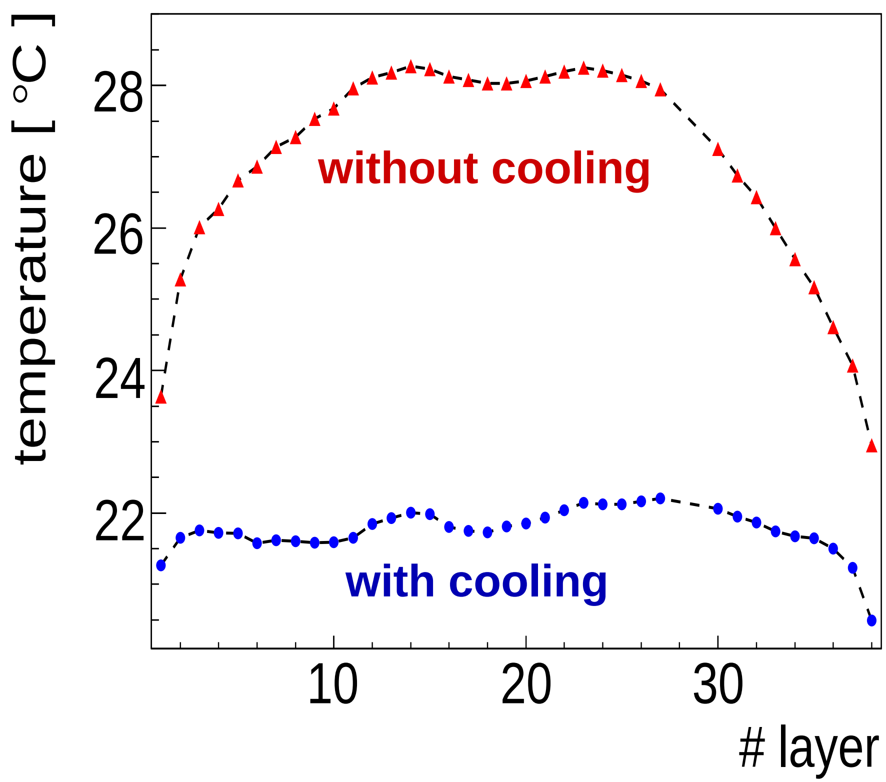
Temperature Correction of SiPM Gain

- **SiPMs operated in Geiger mode: $V_{bias} = V_{breakdown} + \Delta V$ ($\approx 50 - 60V$)**

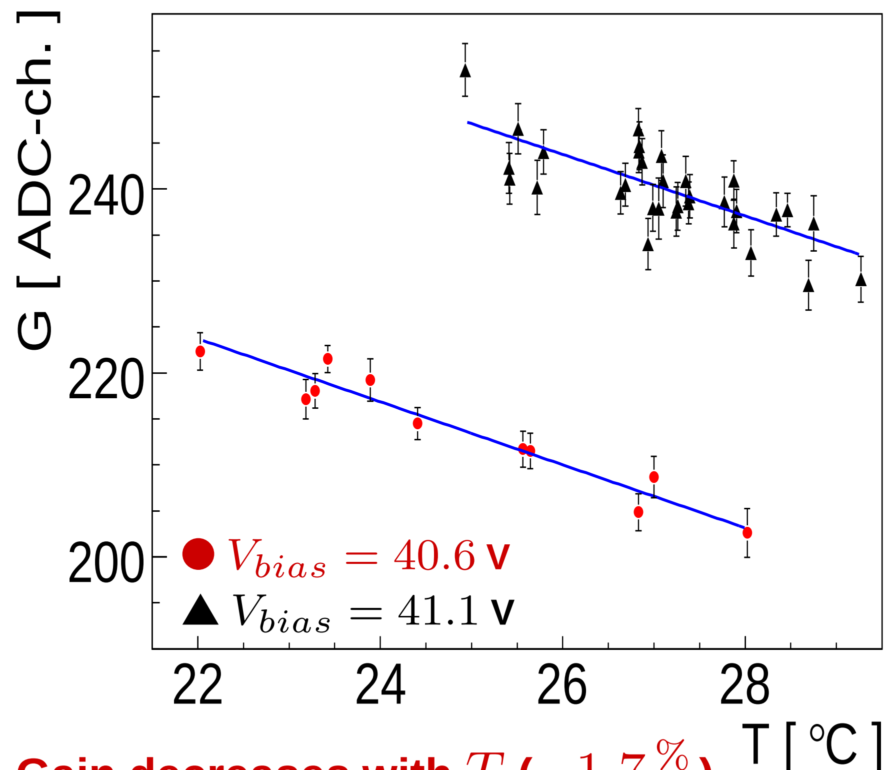
  $V_{breakdown}$ **temperature dependent** $\Longrightarrow \Delta V$ **temperature dependent**

- **Temperature monitoring system implemented**

Temperature profile:



Gain temperature dependence:



Gain decreases with T ($-1.7\frac{\%}{K}$)

- **Temperature correction (also for A_{MIP}) implemented in the analyses presented here**

Hadronic Shower Separation

- **Key feature for particle flow approach (PFA):**

combined Tracking+ECAL+HCAL+Software info for jet energy resolution

cluster reconstruction

charged tracks	γ_s	**neutral hadrons**	
60%	**30%**	**10%**	$\Leftarrow$ **relative contributions to jet structure**

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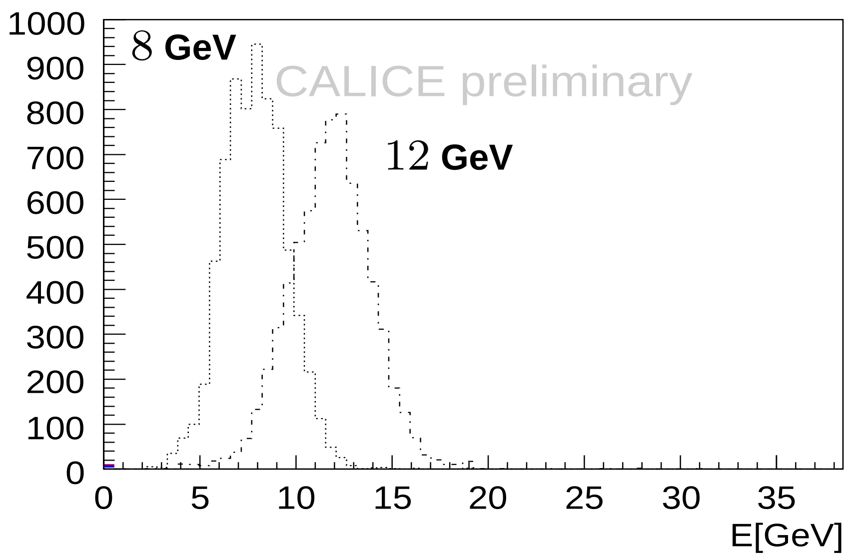

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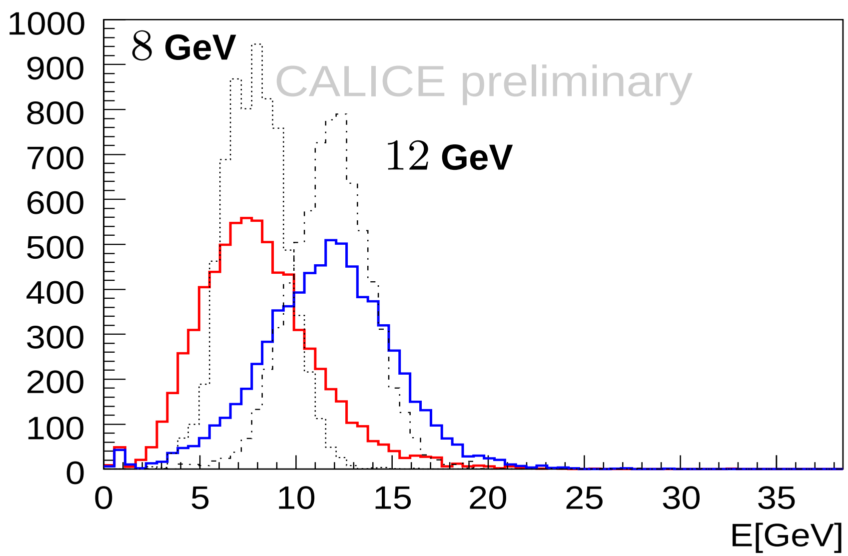

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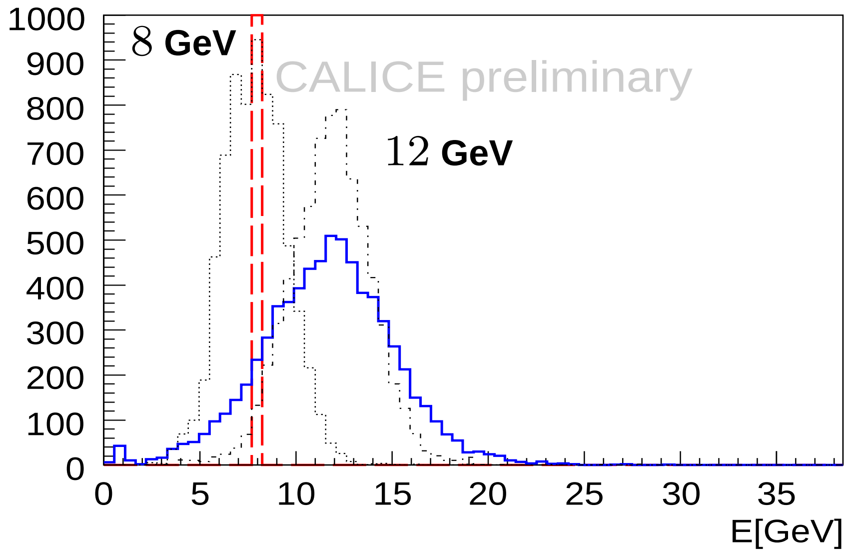
  — assume a PFA scenario:

  charged track + neutral $\hookrightarrow$ fix 1 charged track energy from test-beam energy



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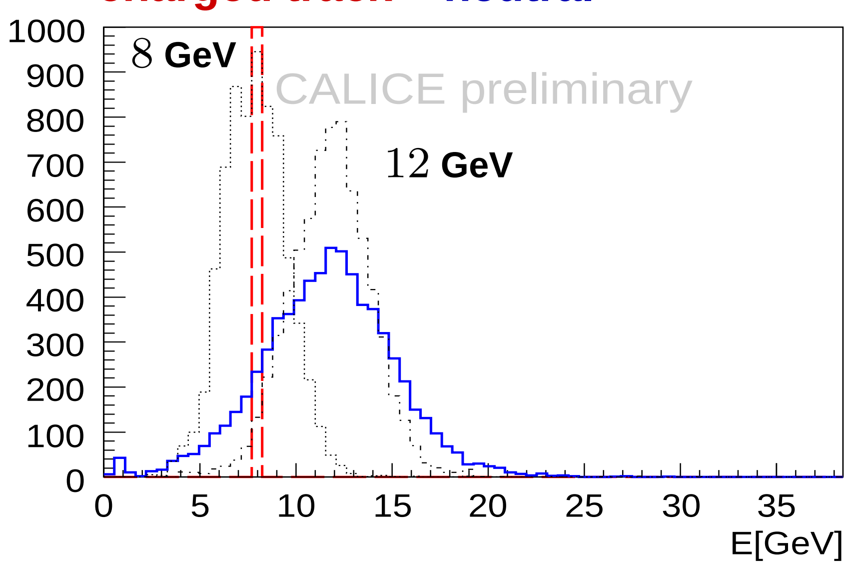

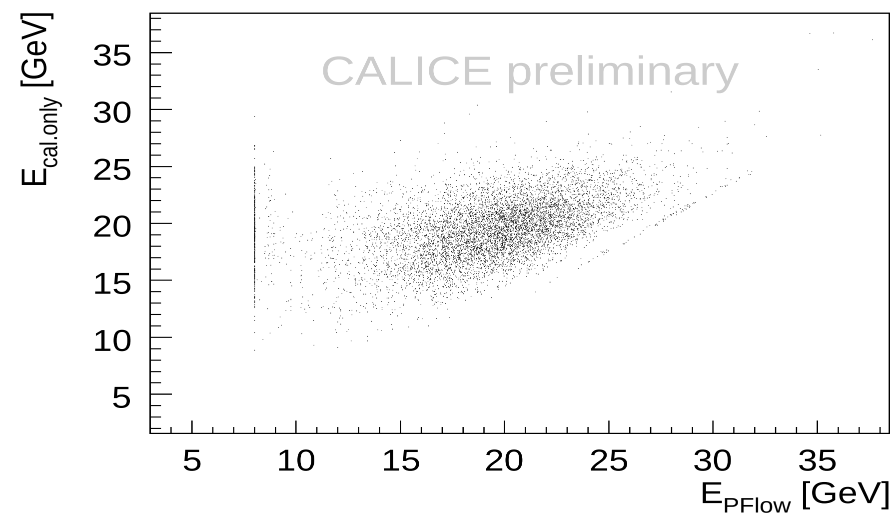

- **Effects of PF approach on $\sum E_{cluster}$ still limited:**

  — too short track impact point distances available so far (only up to $\approx$ 10cm)

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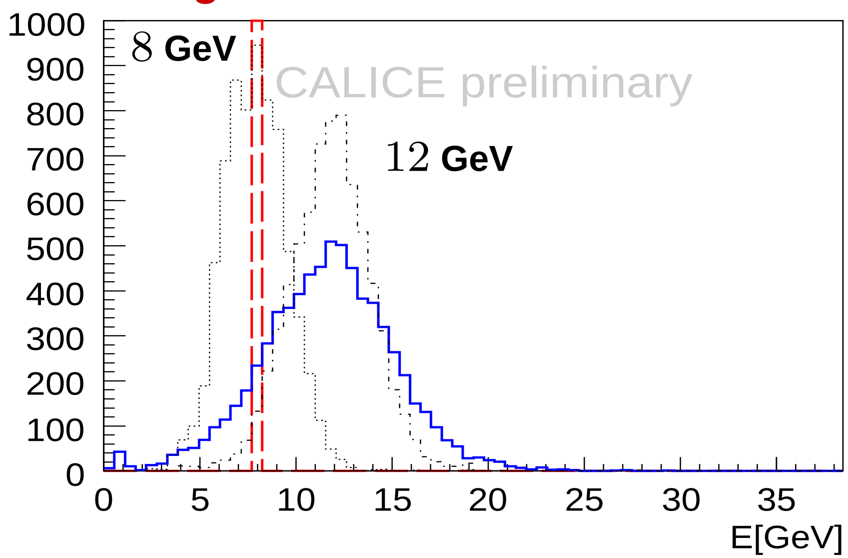

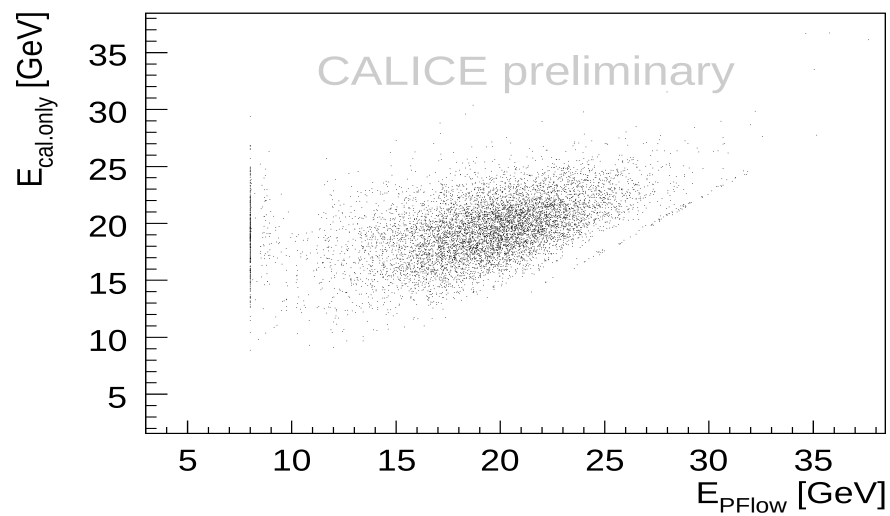

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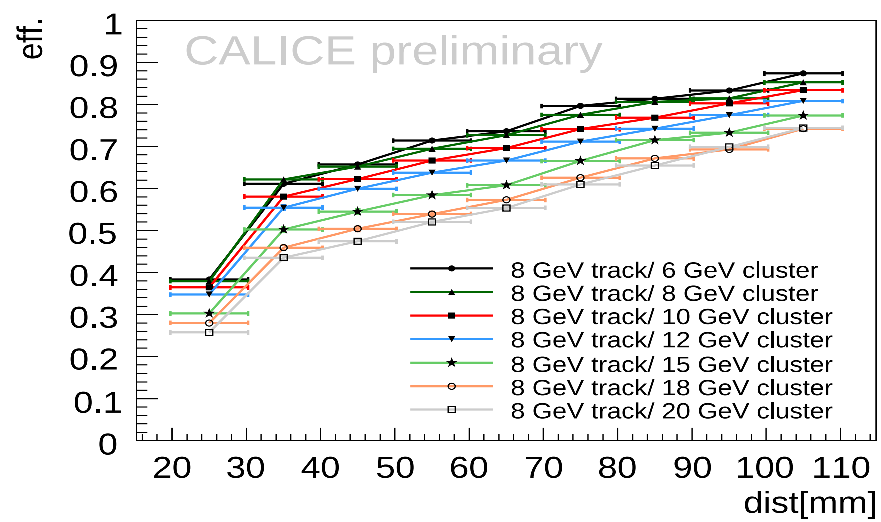

- **Reconstruction algorithm efficiency**

Monte Carlo Physics Model Lists

- **LHEP (Low/High Energy Parameterization)**

— two sets of parameterization of existing data from GHEISHA for E$<$55 GeV and E$>$25 GeV. Randomly pick up one of the two lists in common energy region

- **QGSP (Quark-Gluon String)**

— model for the primary projectile-nucleon collision plus the precompound model for de-excitation of the nucleus. Used for E$>$12 (E$>$20) GeV for protons, neutrons, pions, kaons (other particles). Outside this energy range LHEP is used

- **QGSP_BERT (QGSP + Bertini cascade model)**

— used for E$<$10 GeV for nucleons, pions, kaons and hyperons

— includes remnant nucleus de-excitation, Fermi breakup and fission

- **QGSP_BERT_HP**

— High Precision package for neutron transport used in QGSP_BERT for E$<$100 MeV.

- **QGSP_BIC (QGSP + Binary cascade model)**

— model valid for E$<$3 GeV protons and neutrons, E$<$1.5 GeV pions, and E$<$3 GeV/A light ions. Remnant nucleus de-excitatiion handled by precompound model

- **QGSC**

— QGS for the primary projectile-nucleon collision

— Chiral Invariant Phase Space model for nucleus de-excitation

Birks' Law

- Describes the light output of organic scintillators
- Fluorescence S in general not proportional to energy loss

  $\Rightarrow$ quenching effects between excited molecules

  — with low energy electrons (< 125 KeV)

  — scintillation by heavy ions $<$ than by electrons

- $\Delta S \propto \frac{\Delta E}{1+k_B(\Delta E/\Delta x)}$

  — k_B is the Birks' constant

  $\Rightarrow$ must be determined for each scintillator