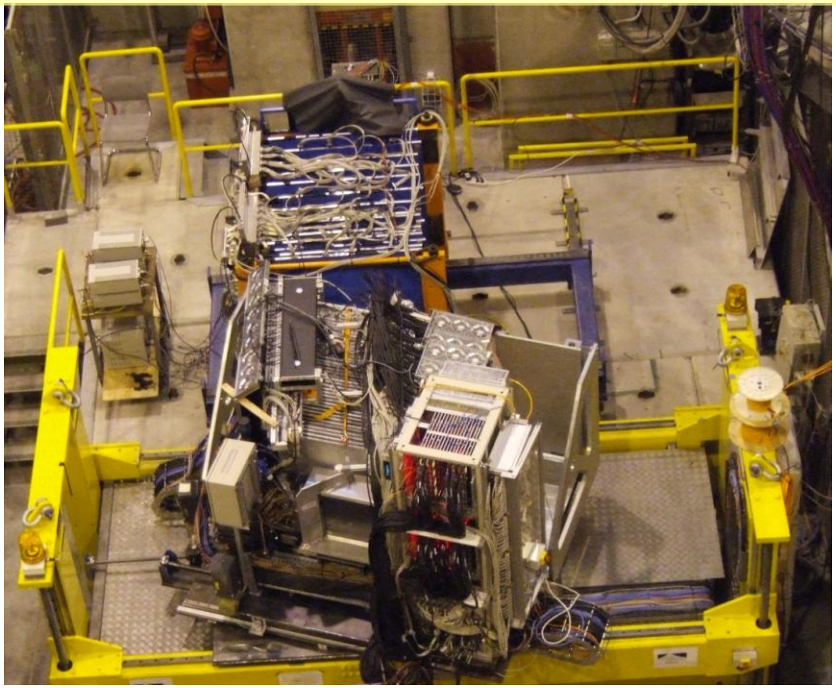
Tests of GEANT4 using the CALICE calorimeters

David Ward

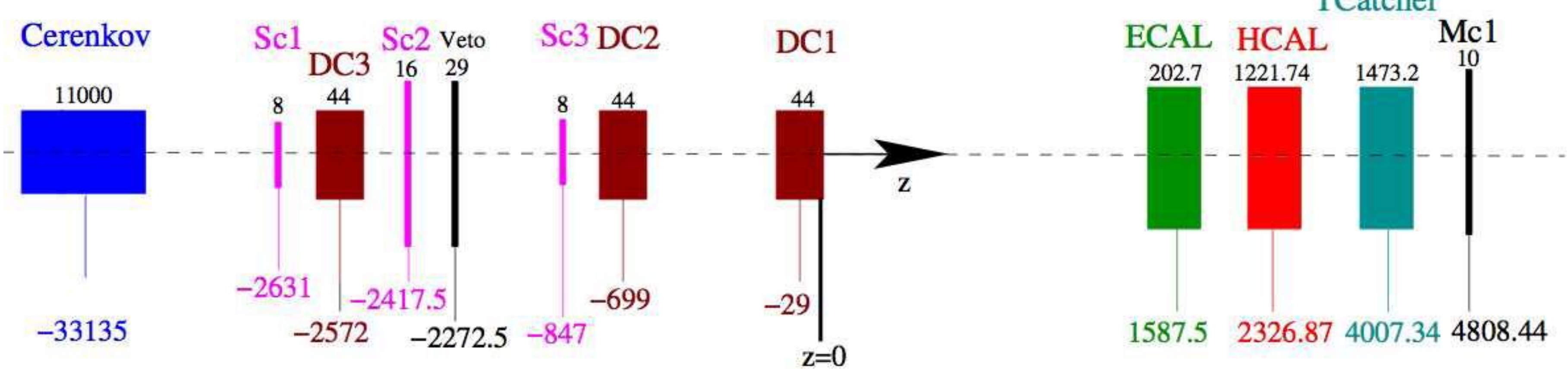
- Electromagnetic particles (μ, e) were used to understand behaviour of the CALICE calorimeters.
- Here focus on hadronic showers + comparison with GEANT4 simulations.
- CALICE calorimeters are highly granular (aimed at Particle Flow)
  - Measure shower profiles with high resolution
  - Determine interaction point accurately
  - Internal structure of shower (e.g. MIP-like track segments)
  - Software compensation
  - PFA tests using data

CALICE test beams

- Major beam tests, using π, μ, e beams:
- 2006-7 SiW ECAL + AHCAL + TCMT @ CERN
- 2008 SiW ECAL + AHCAL + TCMT @ Fermilab
- 2008-9 Scint-W ECAL + AHCAL + TCMT @ Fermilab
- 2010 DHCAL + TCMT @ Fermilab
- 2010 W HCAL @ CERN



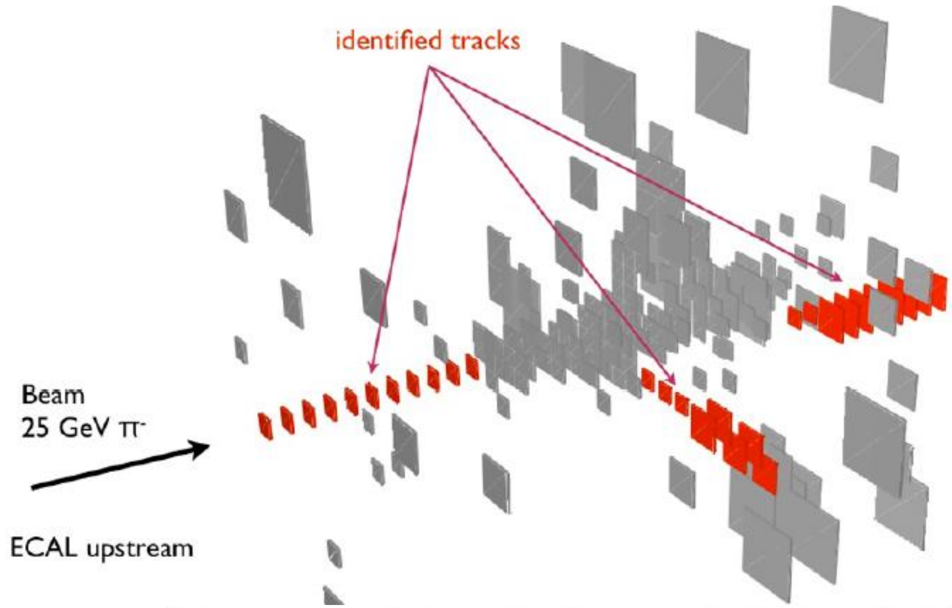
CERN July 2007: TOP view

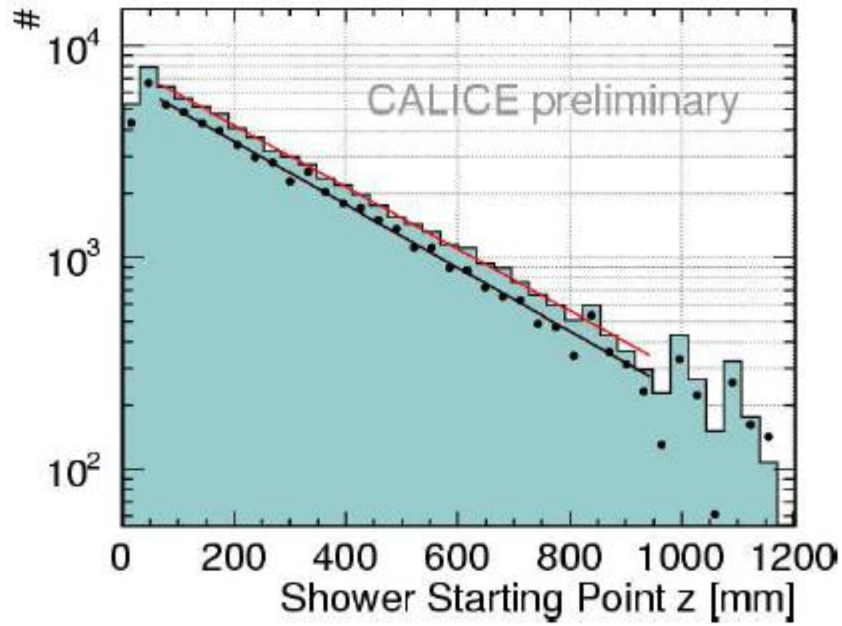


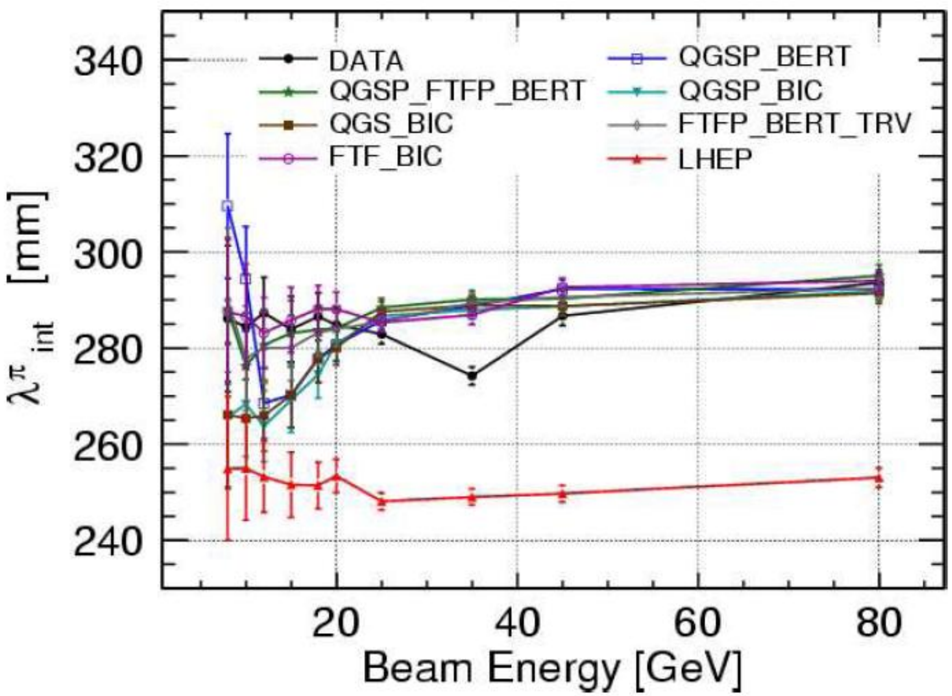
Data and MC

- Show results from 2007 CERN test beam campaign
  - Si-W ECAL 24 X_0, ~1 λ_{int}; 30 layers of 1x1 cm^2 Si pads.
  - Fe-Scintillator analogue HCAL, ~4 λ_{int} ; 38 layers of (mainly) 3x3 cm^2 scintillator tiles with SiPM readout.
  - Fe-Scintillator Tail Catcher + Muon Tracker (TCMT); ~5 λ_{int}; 16 layers of 5 cm scintillator strips.
- Muon beams for calibration; electron beams for testing detector performance.
- Focus here on $\pi^{\pm}$ beams in range 8-80 GeV – key range for jets at LC.
- Compare with GEANT4 using several hadronic physics lists:
  - LHEP, QGSP_BERT, QGSP_BERT, QGSP_FTFP_BERT, FTFP_BERT, FTFP_BERT_TRV, QGSP_BIC, QGS_BIC, FTF_BIC
- Version 4.9.3 (December 2009) unless otherwise stated; some comparisons based on 4.9.2 at this stage.

“Tracking calorimetry”



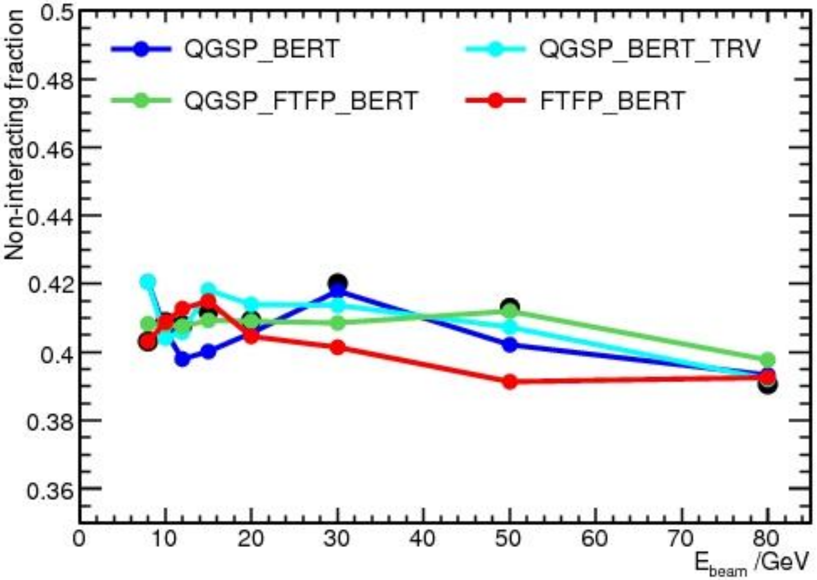


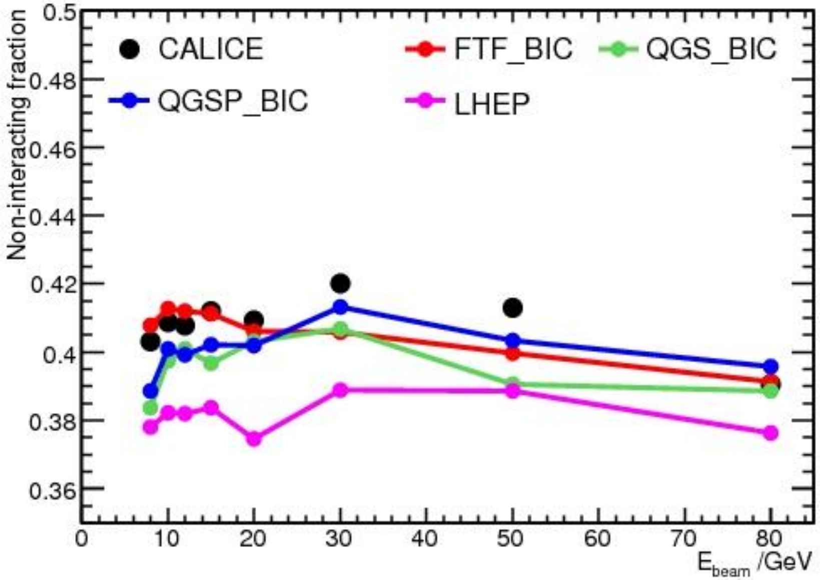


- Can identify shower start with good precision.
- Exponential distribution of start points in the AHCAL
- ⇒ infer effective interaction length.
- Serves as a cross-section check on Fe in GEANT4.
- All models OK, apart from LHEP.

Similarly - probability of not interacting in ECAL

As identified through MIP-like energy deposition in ECAL



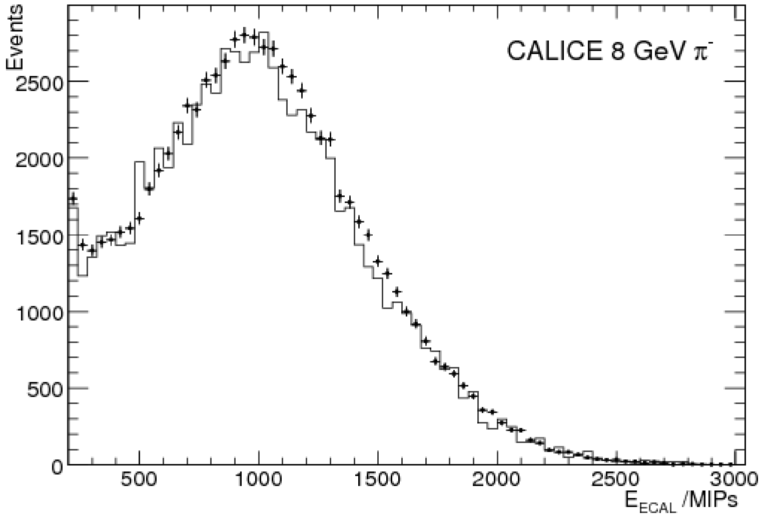


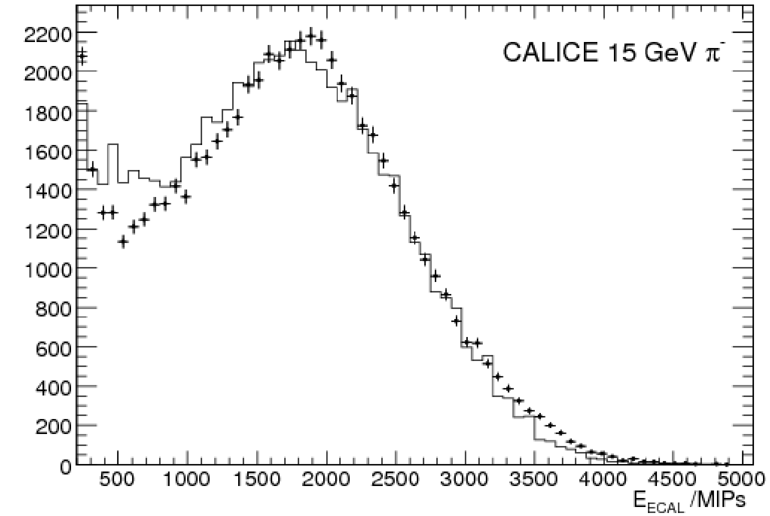
Serves as a test of the GEANT4 cross-sections on Tungsten

Most physics lists within 1-2% of data

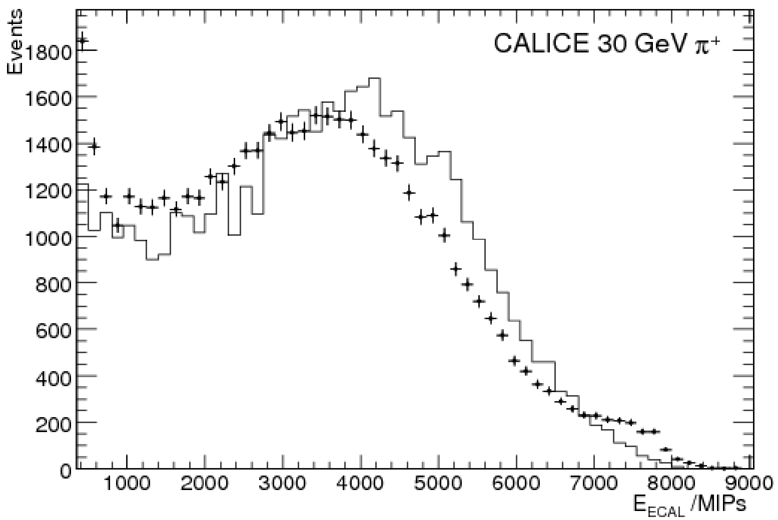
Most conspicuous outlier is LHEP

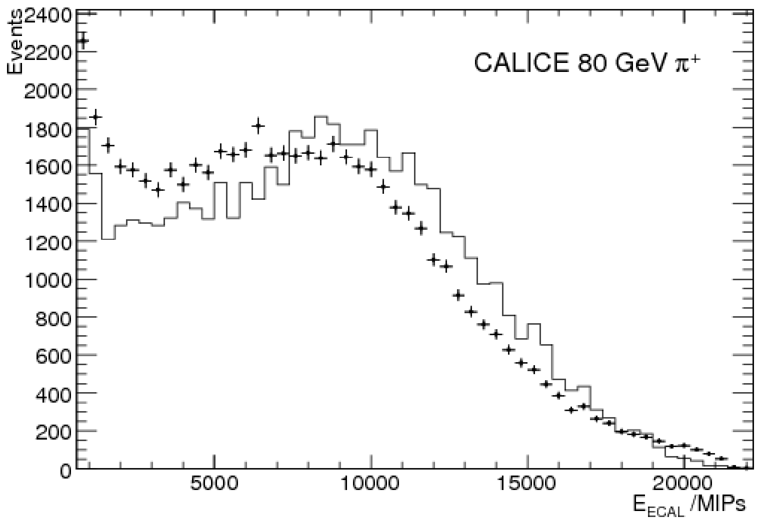
Energy in ECAL (QGSP_BERT physics list)





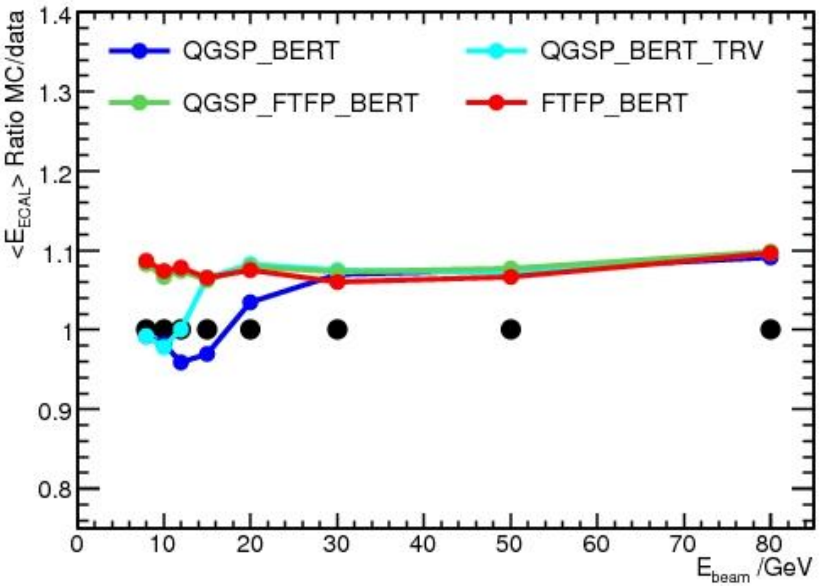
This model looks good at 8 GeV (BERT); less so at high energy (QGS)

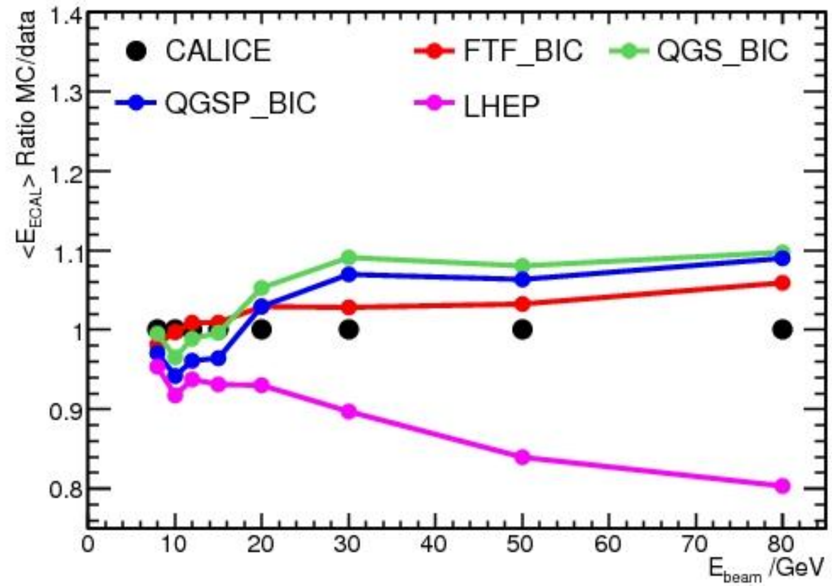




Energy deposited in ECAL

Show trend of <E(MC)>/<E(Data)> vs beam energy

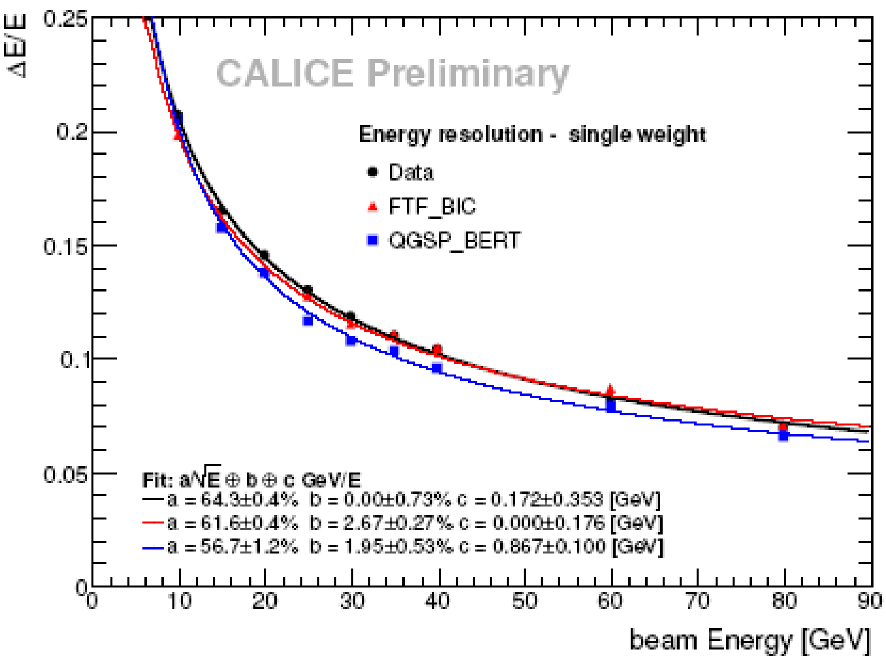


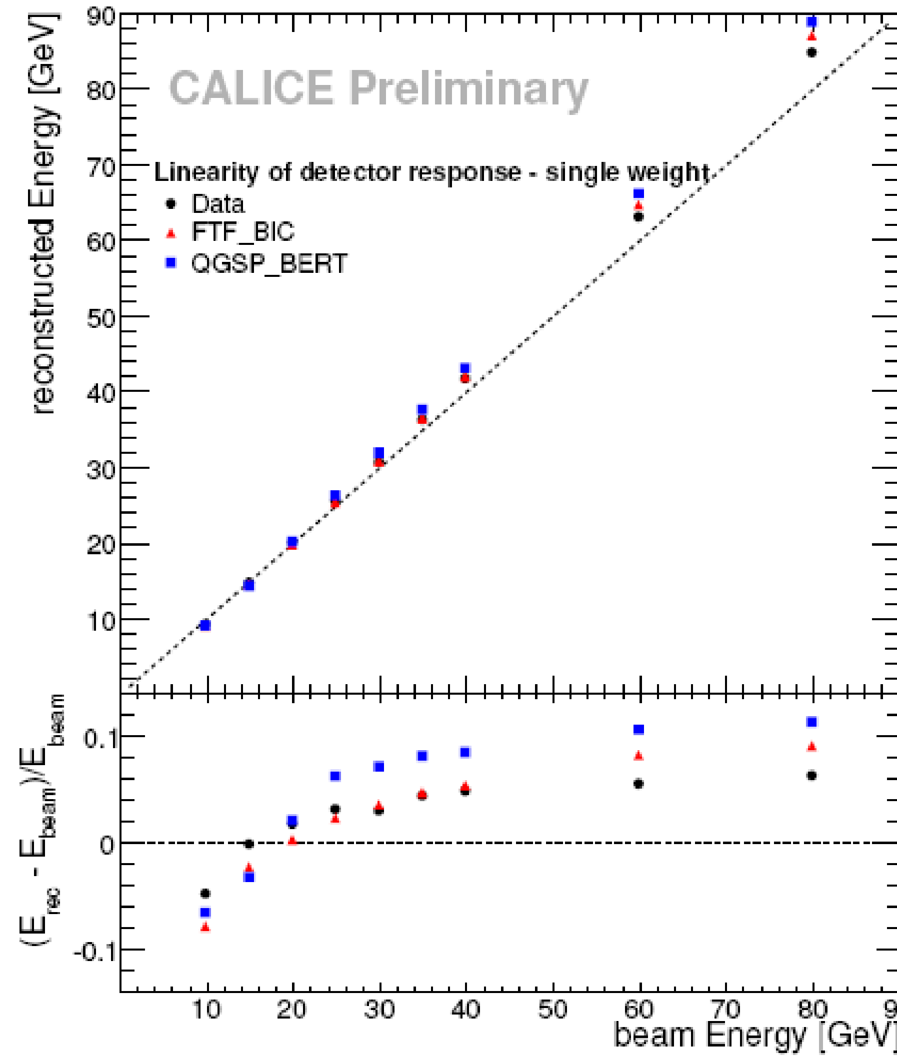


- Steps seen as Geant4 makes transitions between models
- Most models within 10% of data, but tend to overestimate at high energies
- Closest overall seems to be FTF_BIC
- LHEP is a striking outlier, diverging significantly at high energies

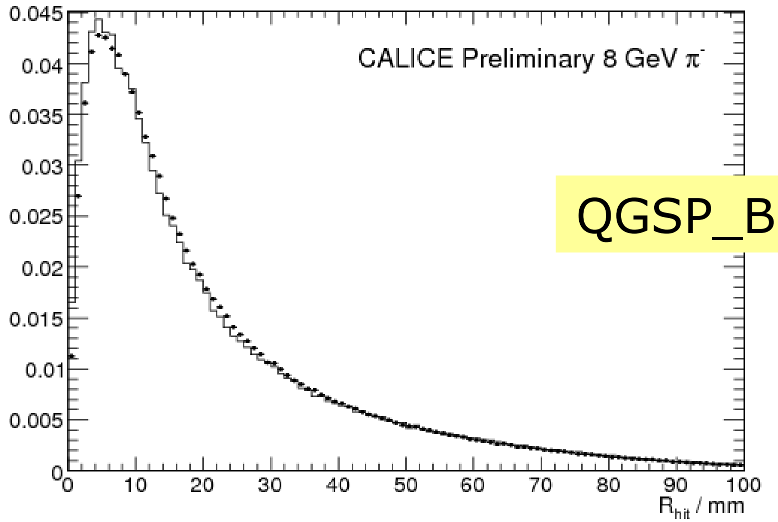
HCAL energy resolution + linearity

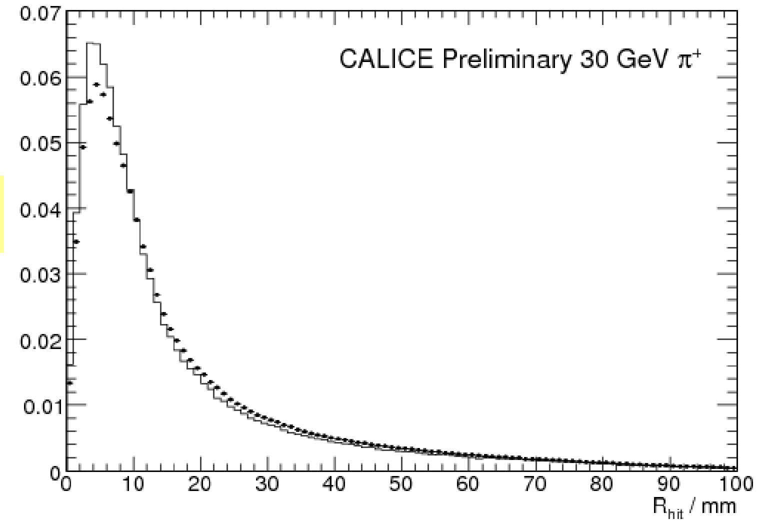
Only two models studied;
But again FTF_BIC seems slightly favoured over QGSP_BERT



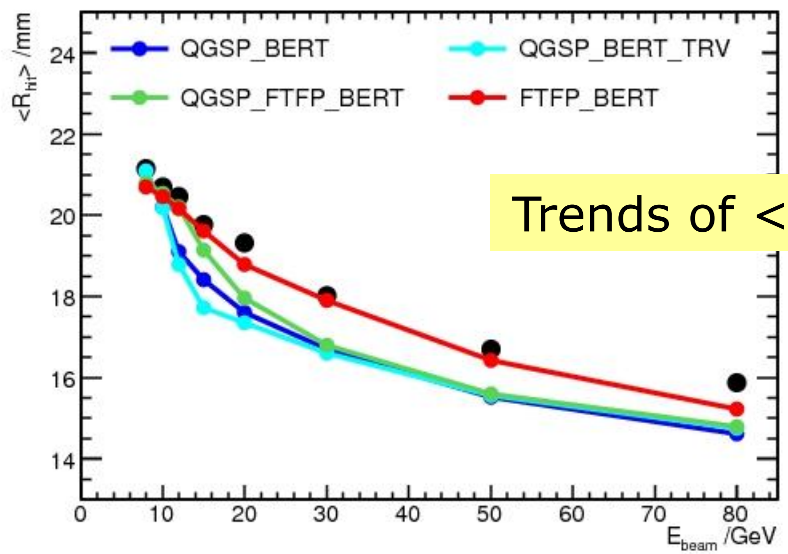


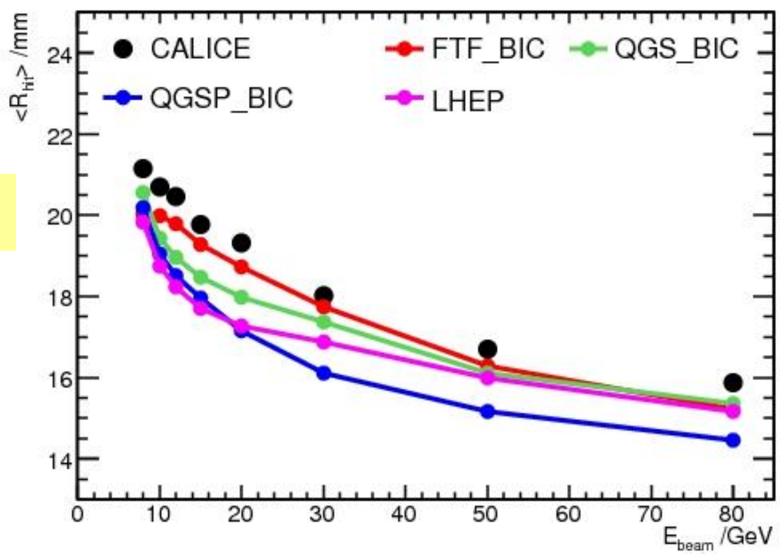
Transverse shower profile in ECAL





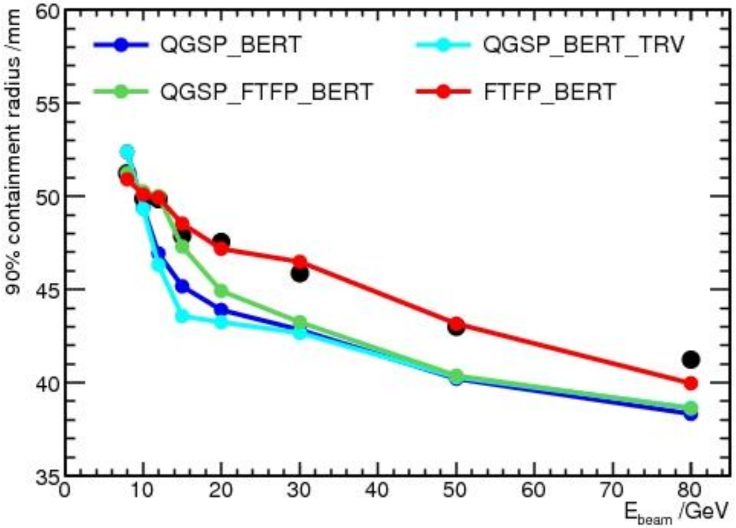
QGSP_BERT

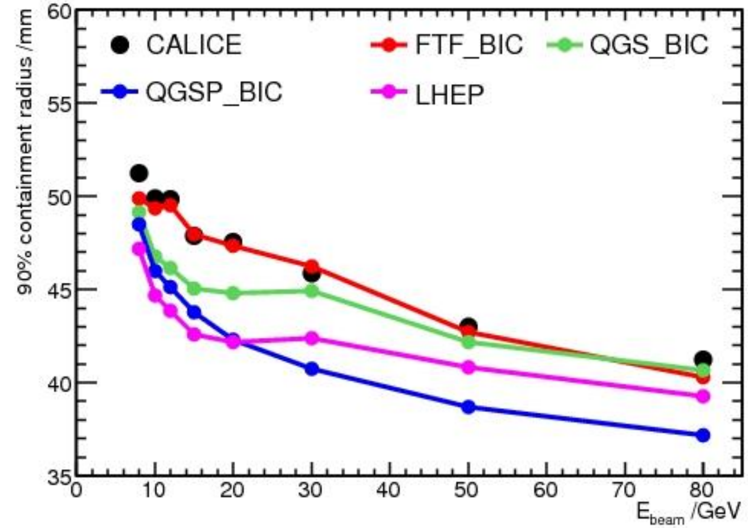




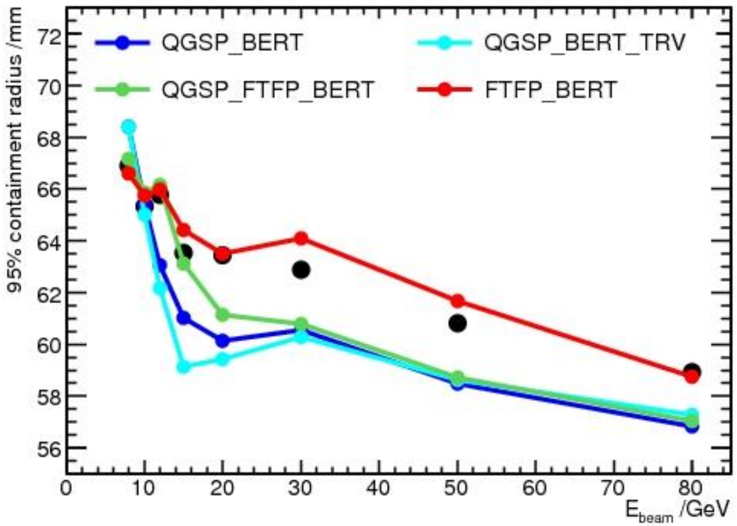
Trends of <R_{hit}>

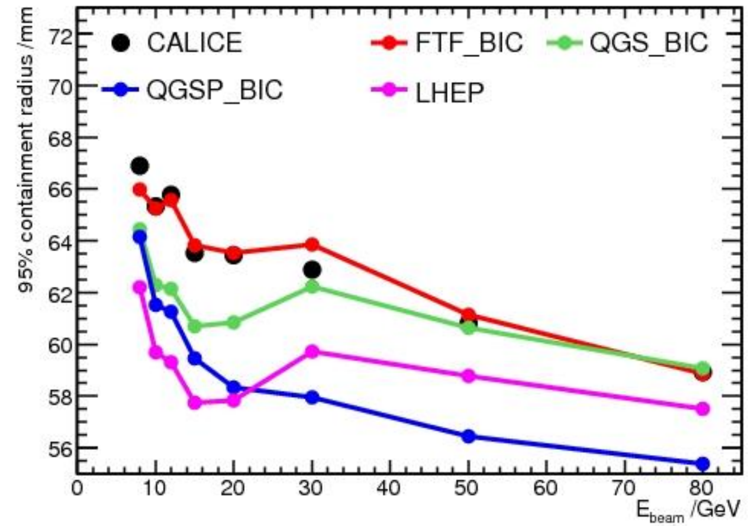
Tails of transverse profiles - ECAL





Radius to confine 90% of shower energy

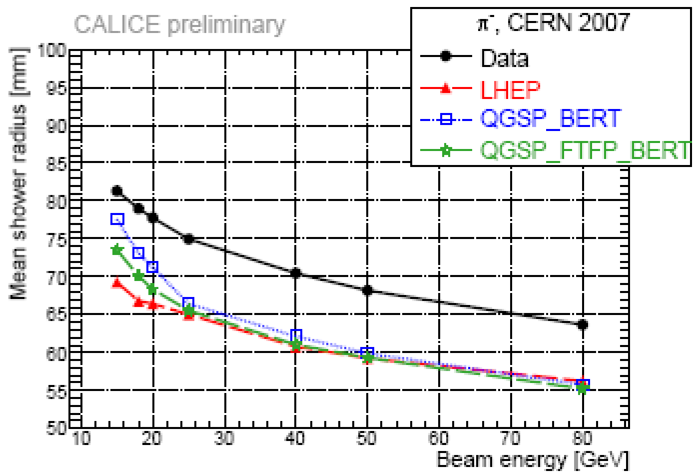




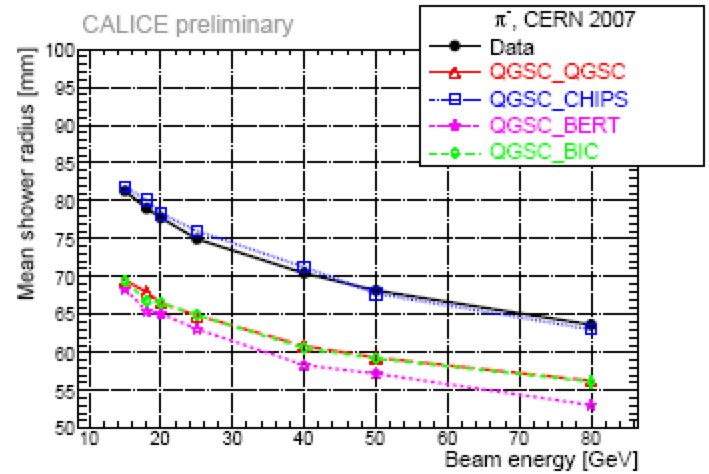
or 95%

Most models underestimate shower width at high energies. FTF lists fit data best

Mean shower radius in HCAL



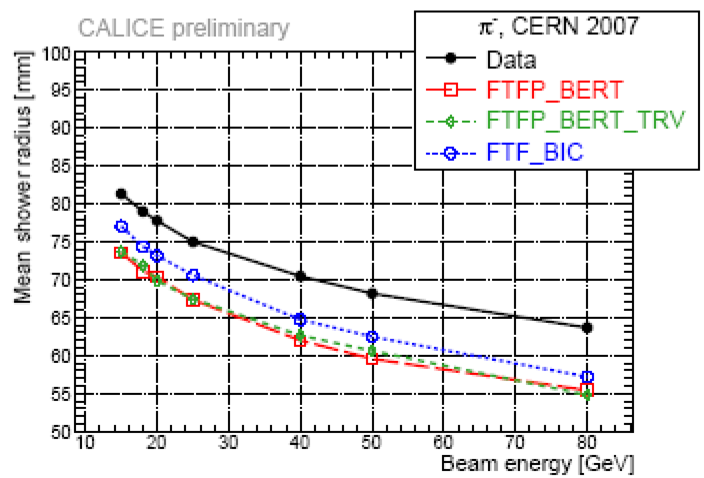
(a)



(b)

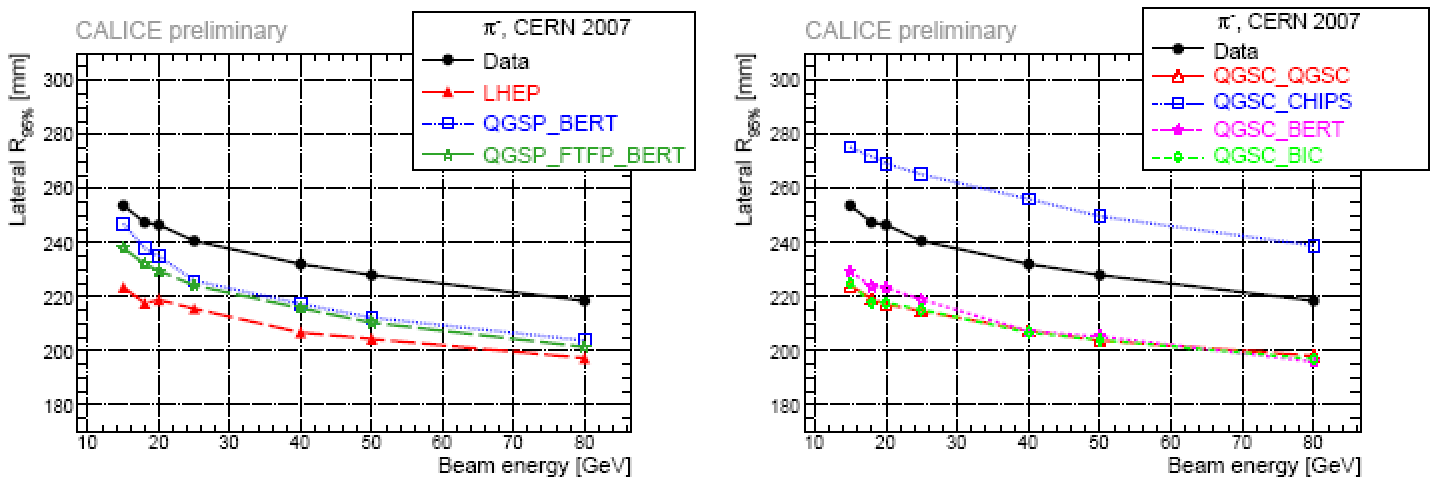
Most physics lists give too small shower radius

QGSC_CHIPS close



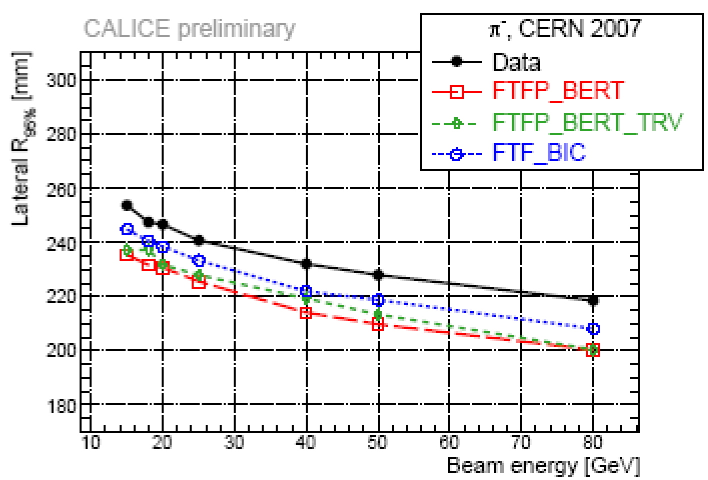
GEANT 4.9.2 used

95% containment radius in HCAL



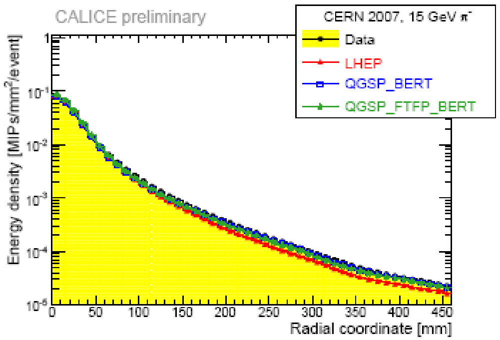
(a) (b)

Most physics lists underestimate tail.
But QGSC_CHIPS overestimates.
FTF_BIC closest.

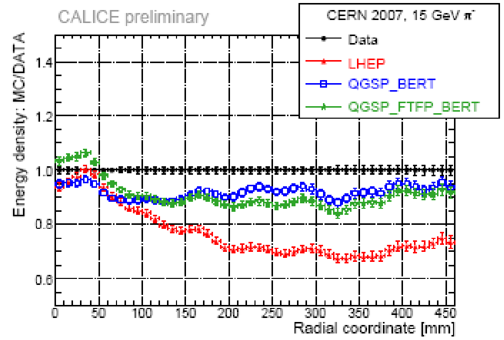


GEANT 4.9.2 used

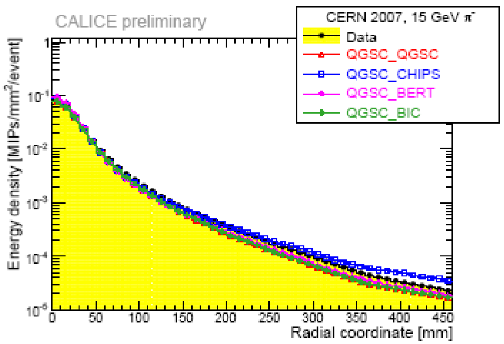
Transverse profiles in AHCAL



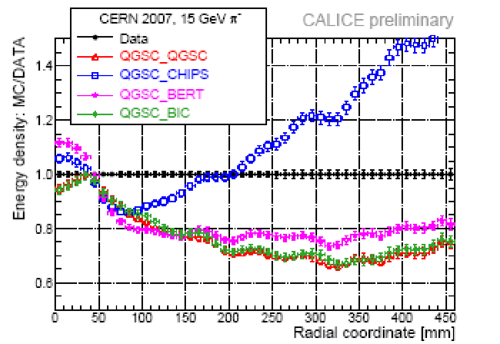
(a)



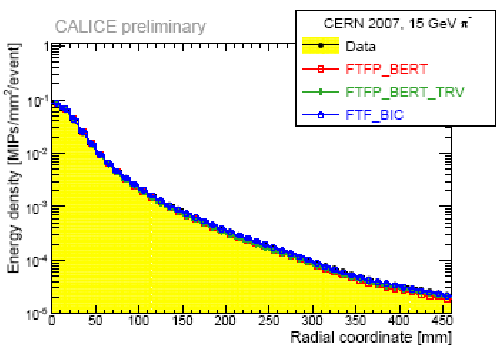
(b)



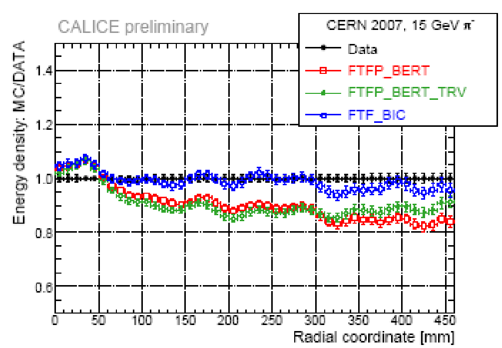
(c)



(d)



(e)



(f)

- Most physics lists give too small shower radius and underestimate tail.
- QGSC_CHIPS gets radius right, but shape is all wrong.
- FTF_BIC best in the far tail.
- Important not to put too much emphasis on any single observable; no physics list gets everything right.

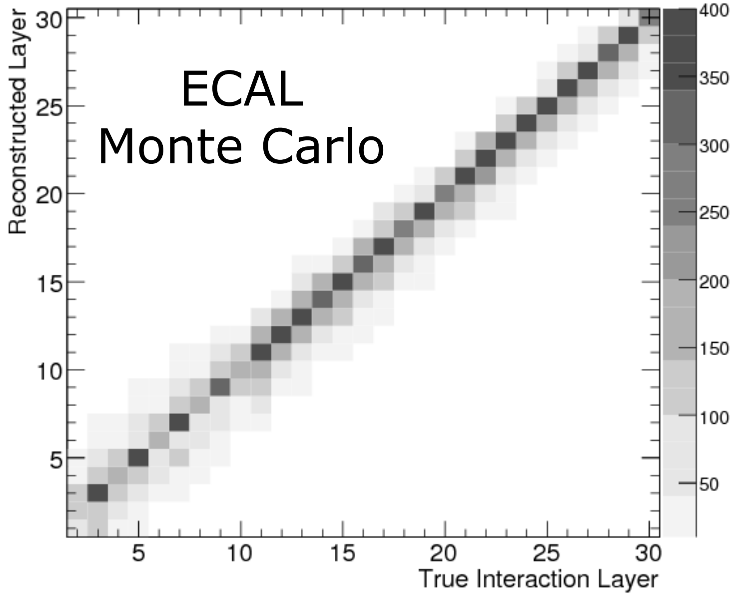
GEANT 4.9.2 used

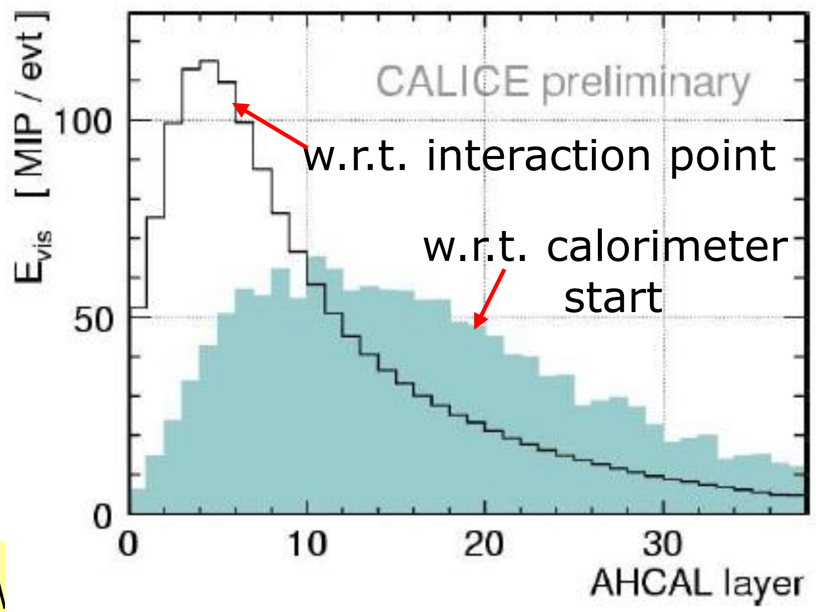
CALICE Calorimeter for LC

UNIVERSITY OF CAMBRIDGE

Longitudinal shower profile

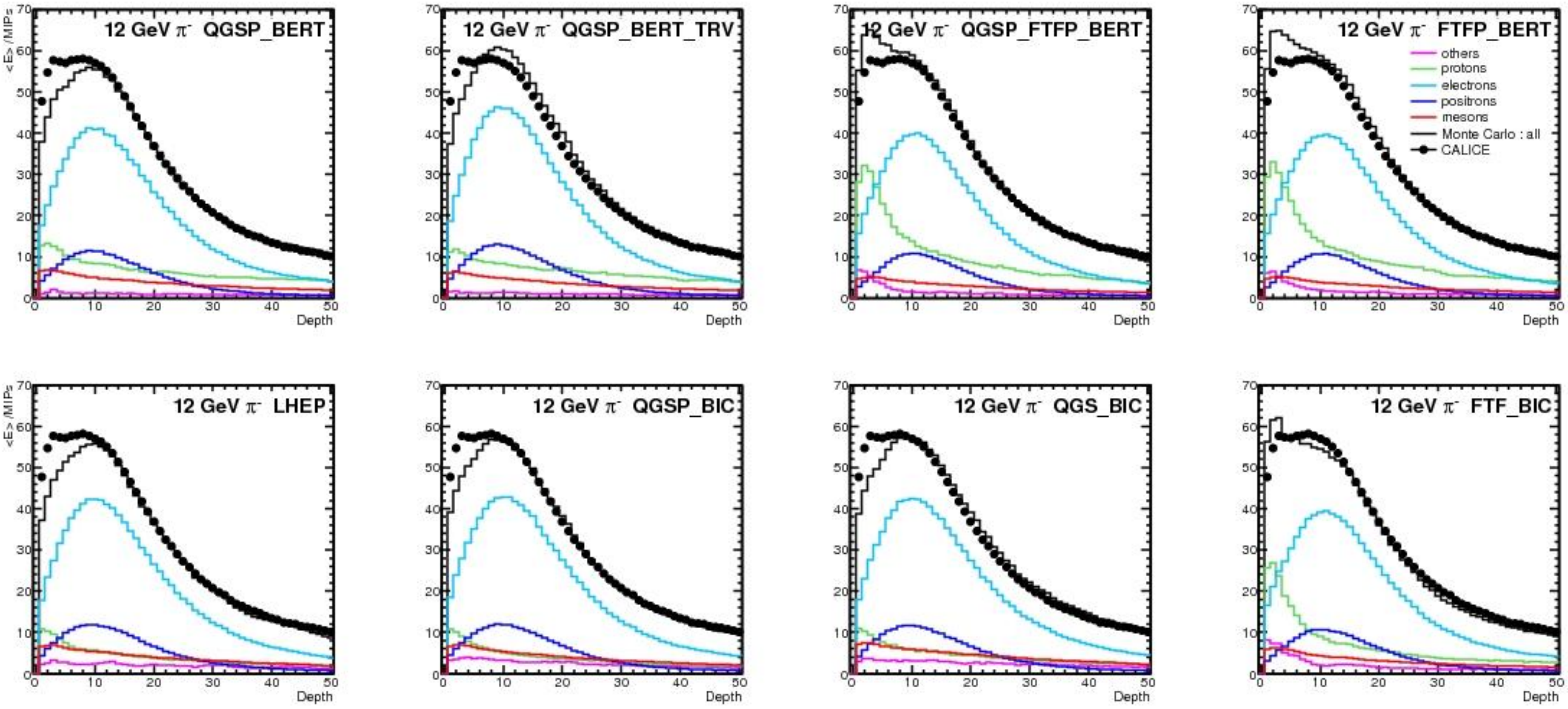
- The observed longitudinal shower shape reflects a convolution of the distribution of shower starting points with the true shower shape.
- High granularity allows us to identify the shower start to within ± 1 layers typically.
- Can then measure shower longitudinal development w.r.t. this point.
- Look at ECAL first. Restrict study to showers starting in first 10 layers of ECAL, so that almost 1 λ_{int} in the ECAL is available to develop the shower. And $\sim 20X_0$ so that photons in initial interaction can shower fully.





Shower profiles w.r.t. interaction point

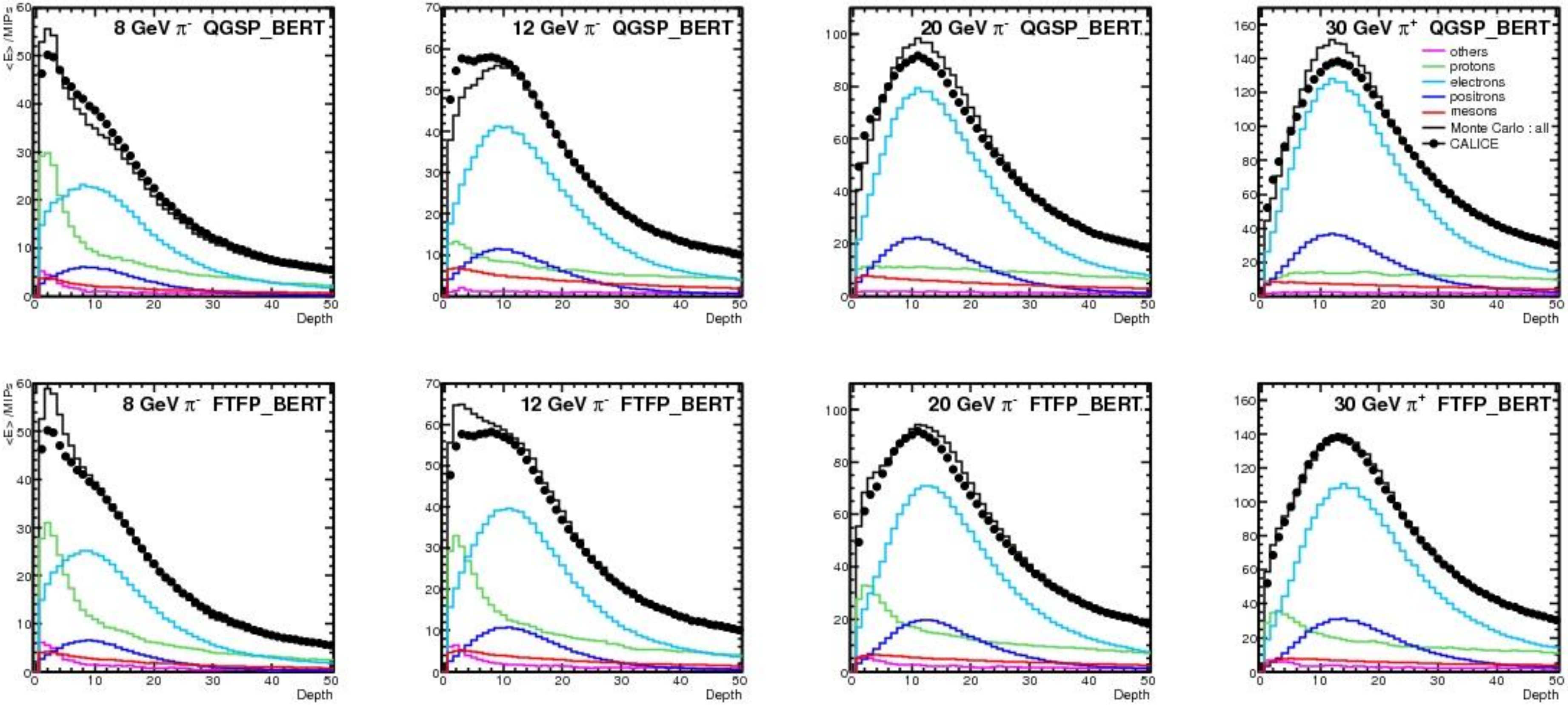
12 GeV data compared to 8 physics lists



In simulation, can record hit energies associated with each particle species.
Note that "mesons" (π, μ, K), $e^{\pm}$ and protons have distinctive shower profiles.
No physics list completely fits the data.

Shower profiles w.r.t. interaction point

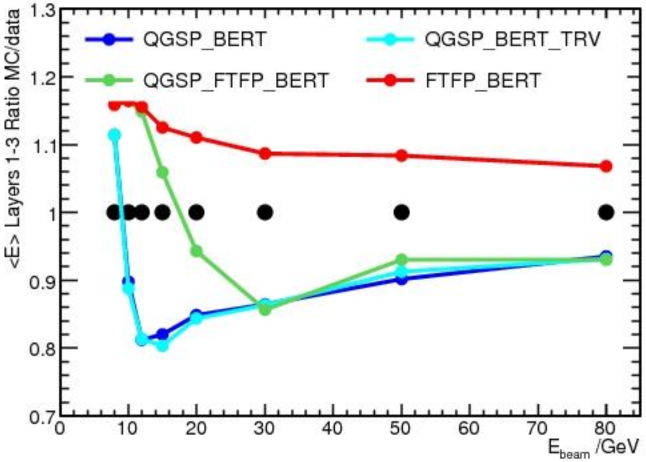
Compare two physics lists at 4 energies

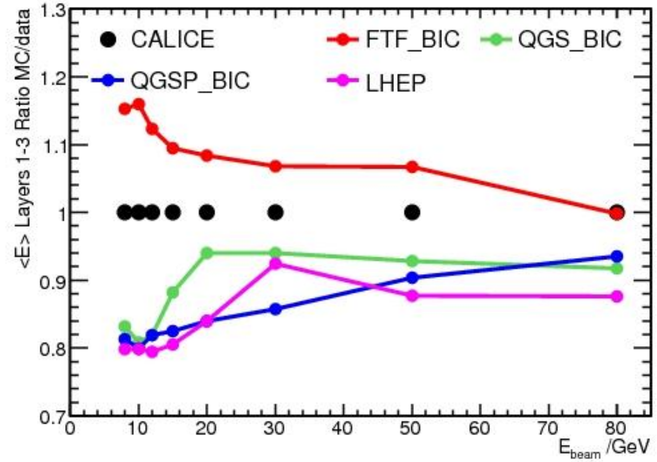


Three main components can be observed:

- Short range component (mainly protons; nuclear spallation)
- Electromagnetic component
- Longer range components; mesons + MIP-like protons

Focus on different regions of the shower:



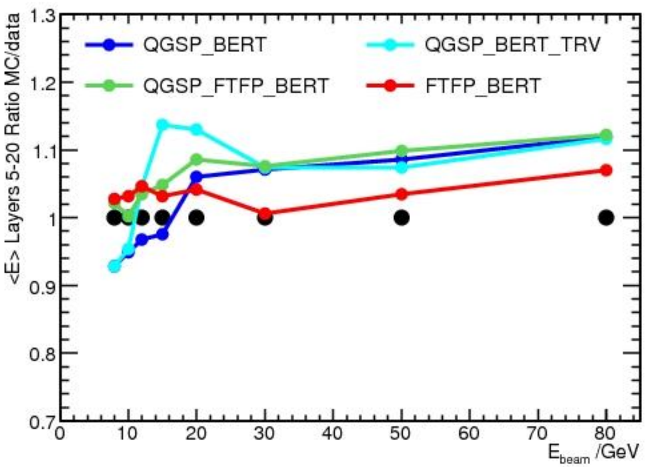


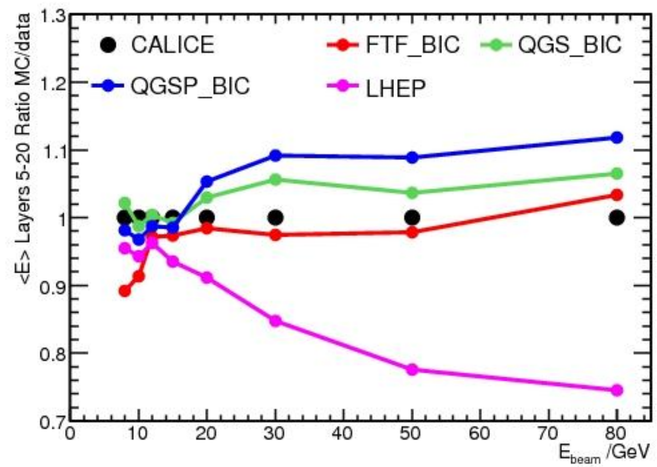
Layers 1-3

Nuclear fragments

No physics list is really successful.

Up to 20% disagreements





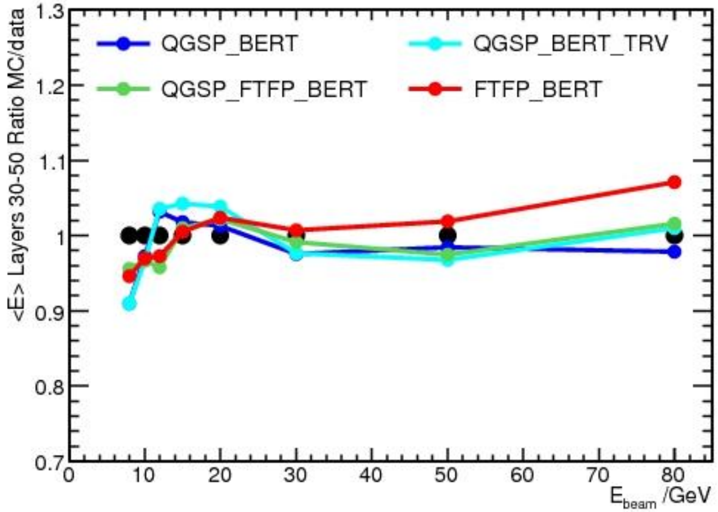
Layers 5-20

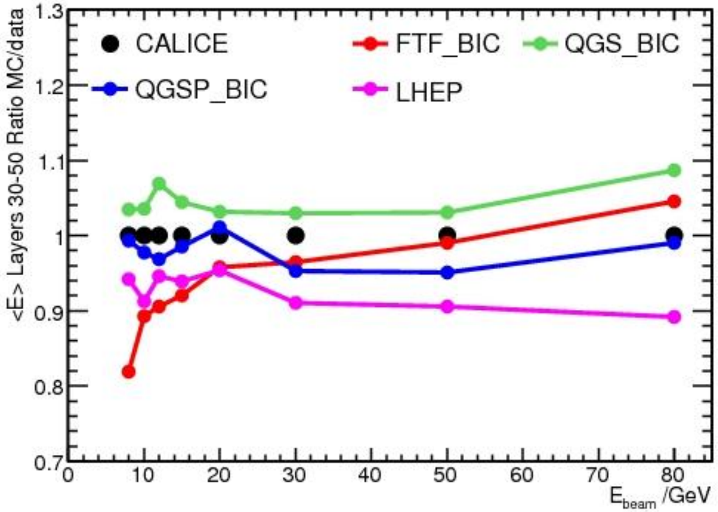
Electromagnetic

FTF lists seem best

LHEP fails badly

… continued …





Layers 30-50

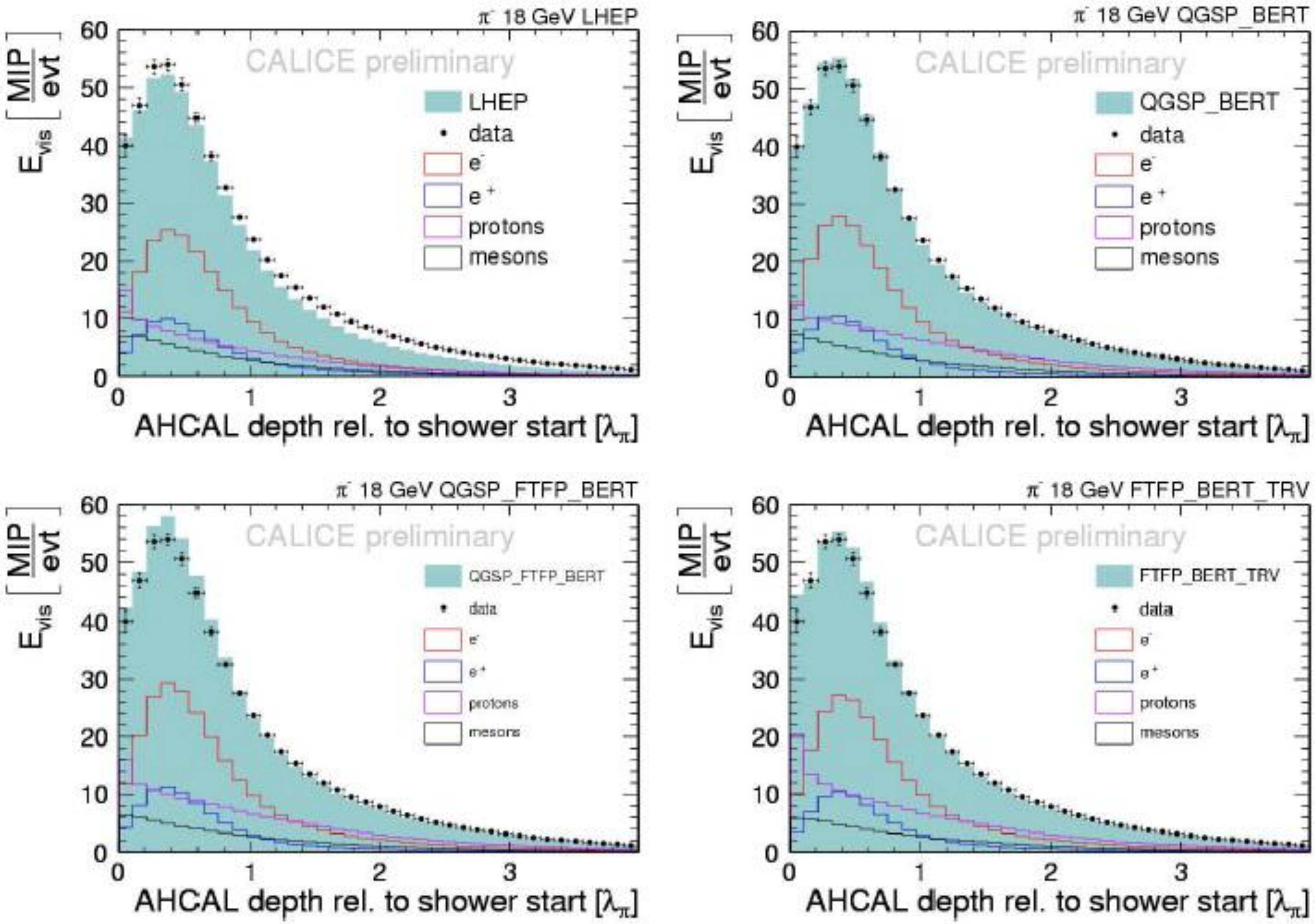
Mainly hadron dominated

Most models within ~10% of data

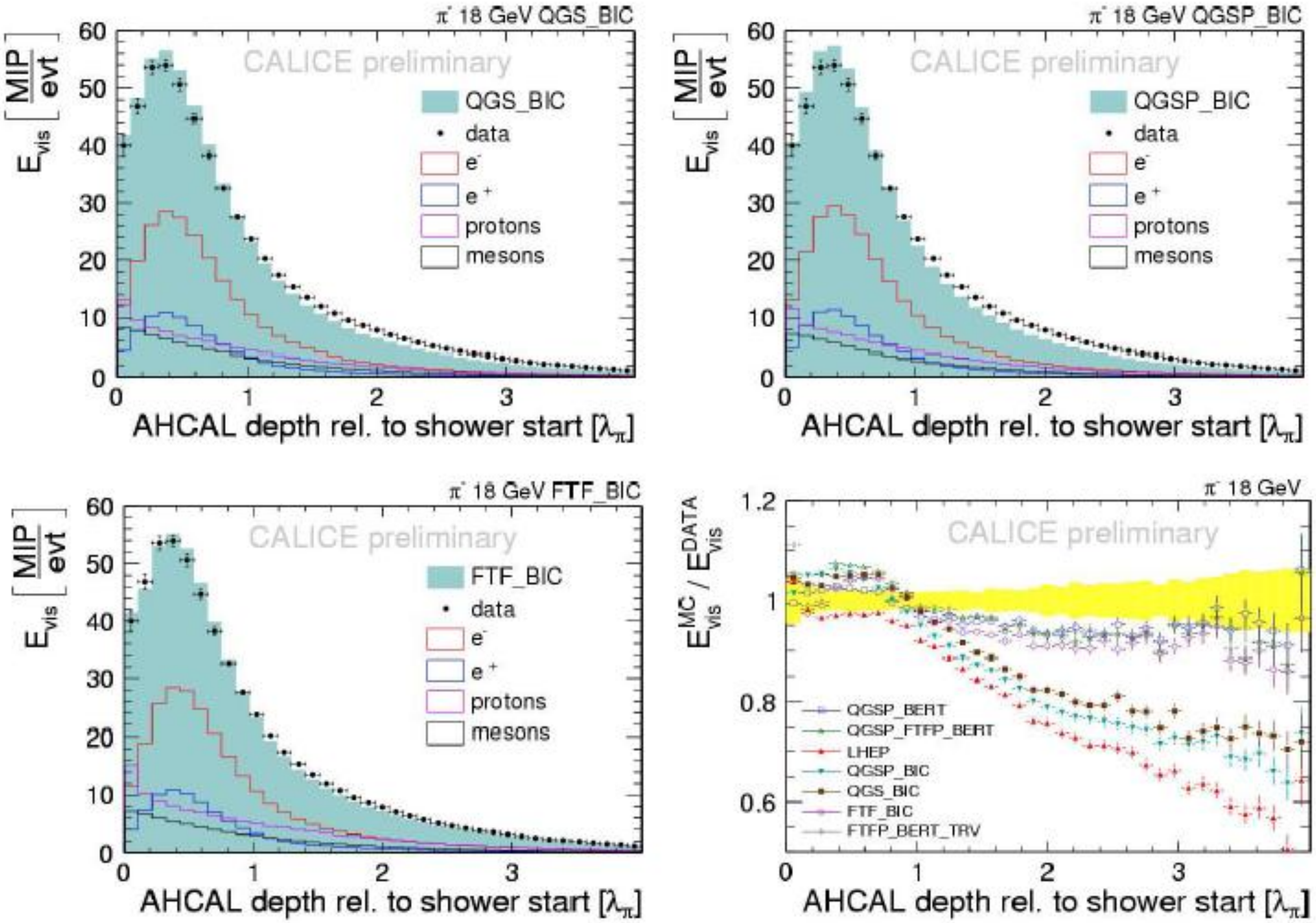
QGSP models slightly favoured

Likewise in HCAL (18 GeV)

Requiring showers to start in first 5 layers of HCAL



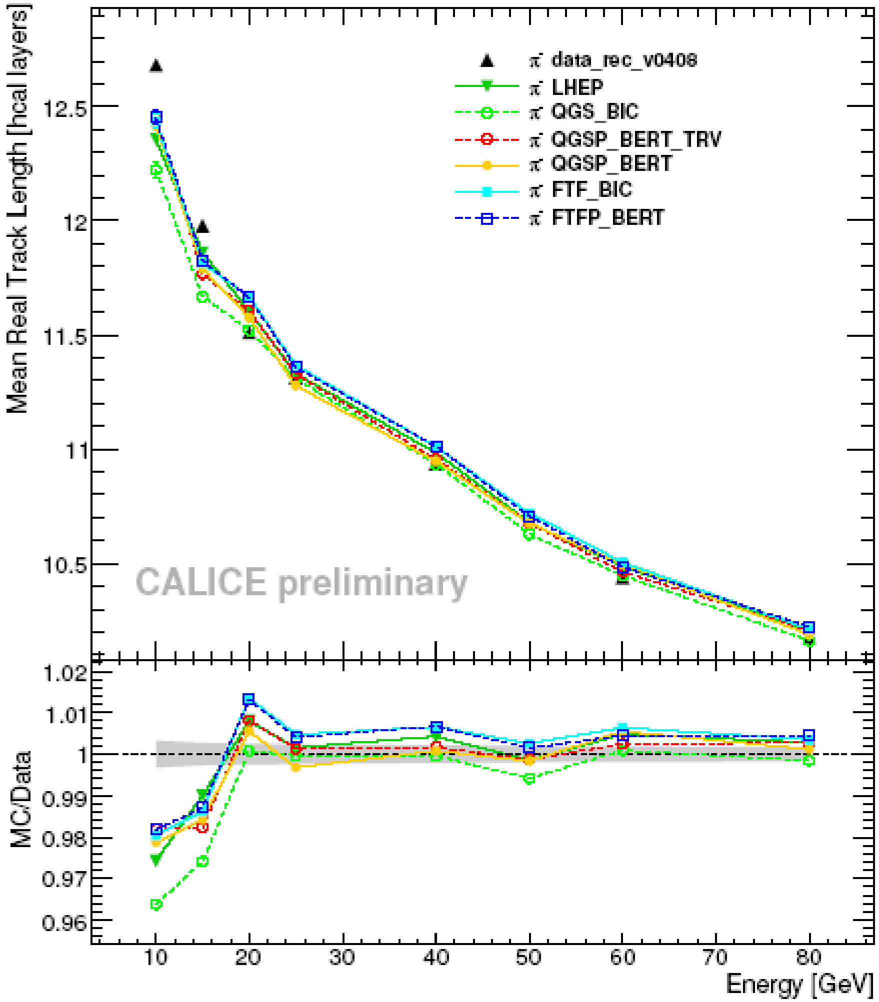
Continued…



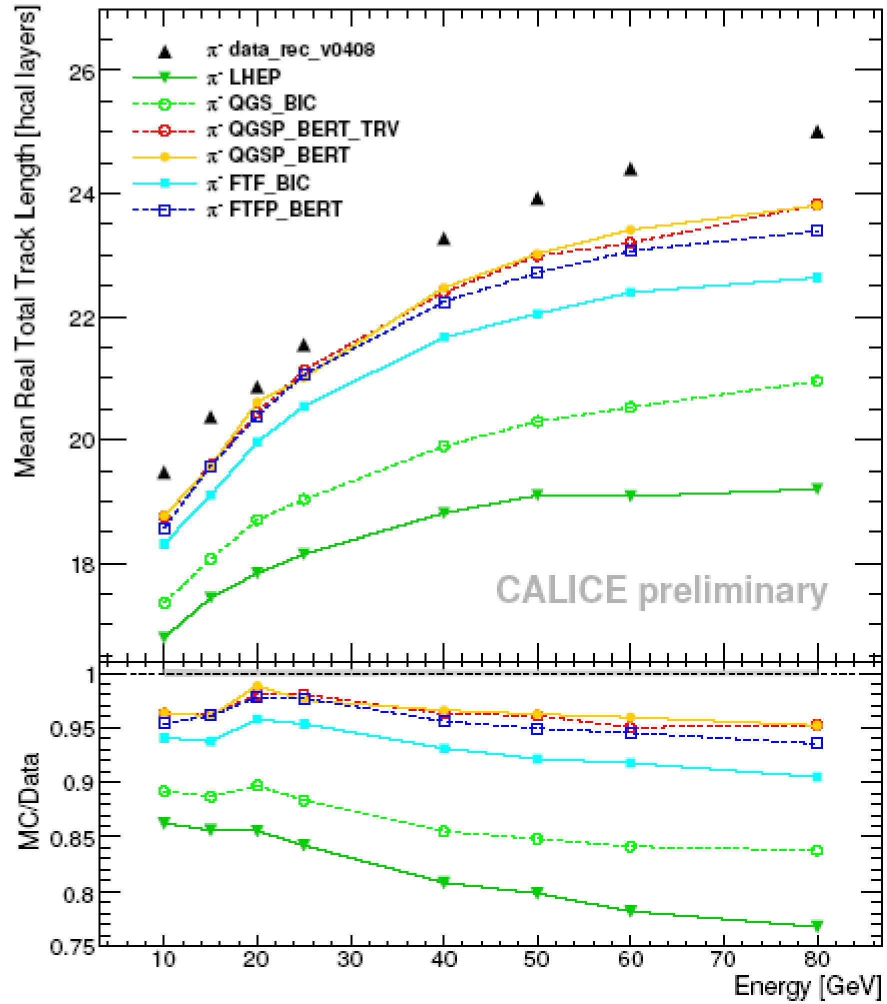
HCAL not so discriminating between components, but similar effects seen to ECAL.
LHEP especially disfavoured; also QGS(P)_BIC less good in HCAL.
Others roughly equally successful.

Track segments

Identify tracks of MIP-like hits in the HCAL. LHEP, QGS_BIC again disfavoured

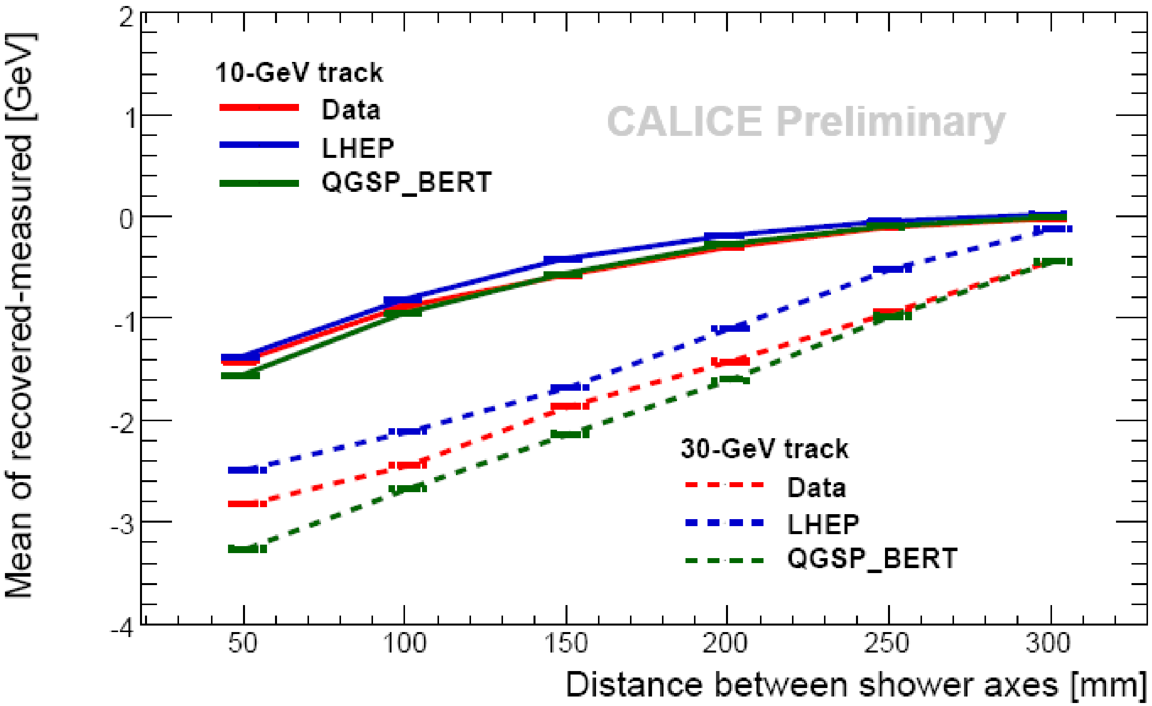


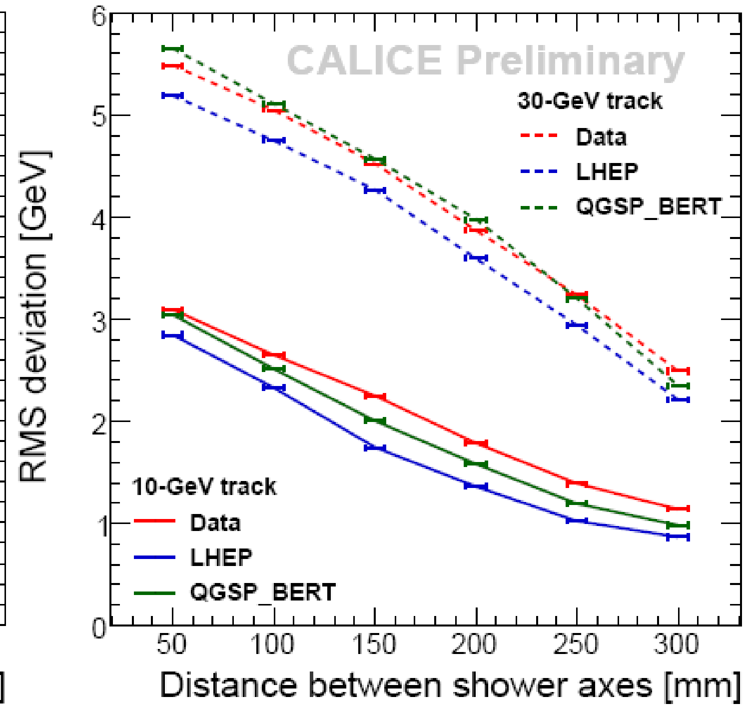
(a) Average track length.



(c) Average of sum of the length of all tracks per event.

PandoraPFA tests

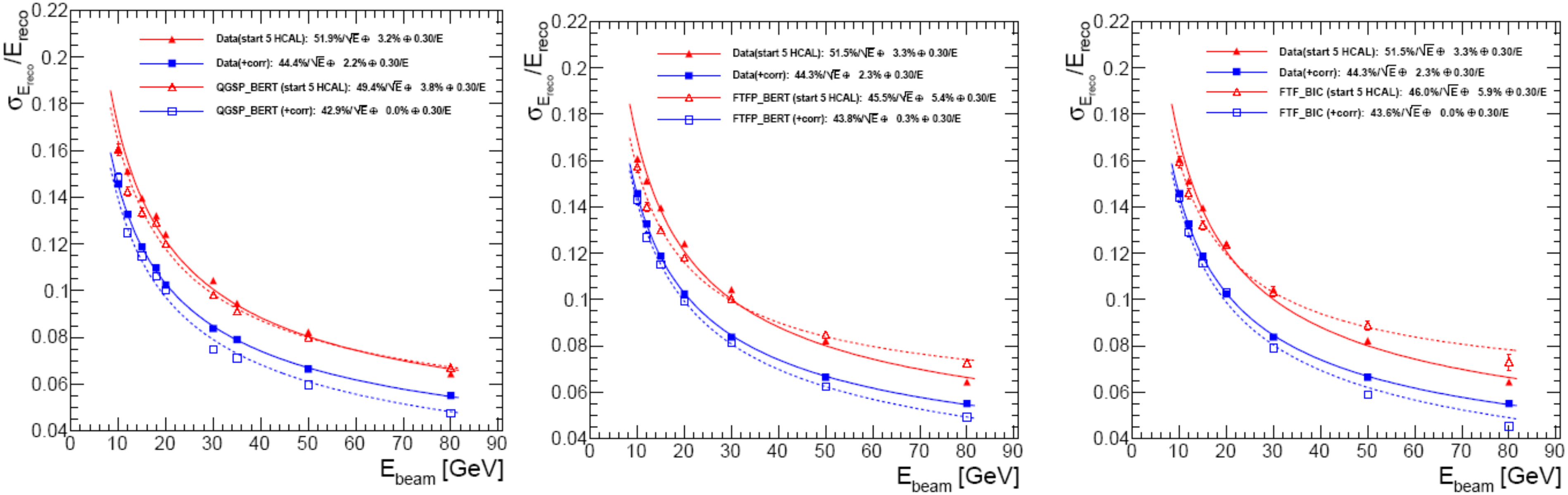




- Superimpose two showers from data with various transverse separations
  - One 10 or 30 GeV π^-
  - One 10 GeV "neutral" – π^- without its incident track segment
- Run PandoraPFA and look at reconstruction of the neutral cluster
- Look at offset and resolution (i.e. confusion) w.r.t. expected energy
- Neither physics list perfect, but QGSP_BERT certainly better then LHEP

GEANT 4.9.2 used

Software compensation



- $e/\pi \neq 1$ in CALICE calorimeters
- Several approaches to software compensation studied
- One example shown above
- Basic idea is that e/m parts of showers are denser, so use weighting of hits to energy density
- Typically achieve relative improvement of ~10-20% in energy resolution.
- Improvement is modelled reasonably well, but not perfectly, by typical GEANT4 models

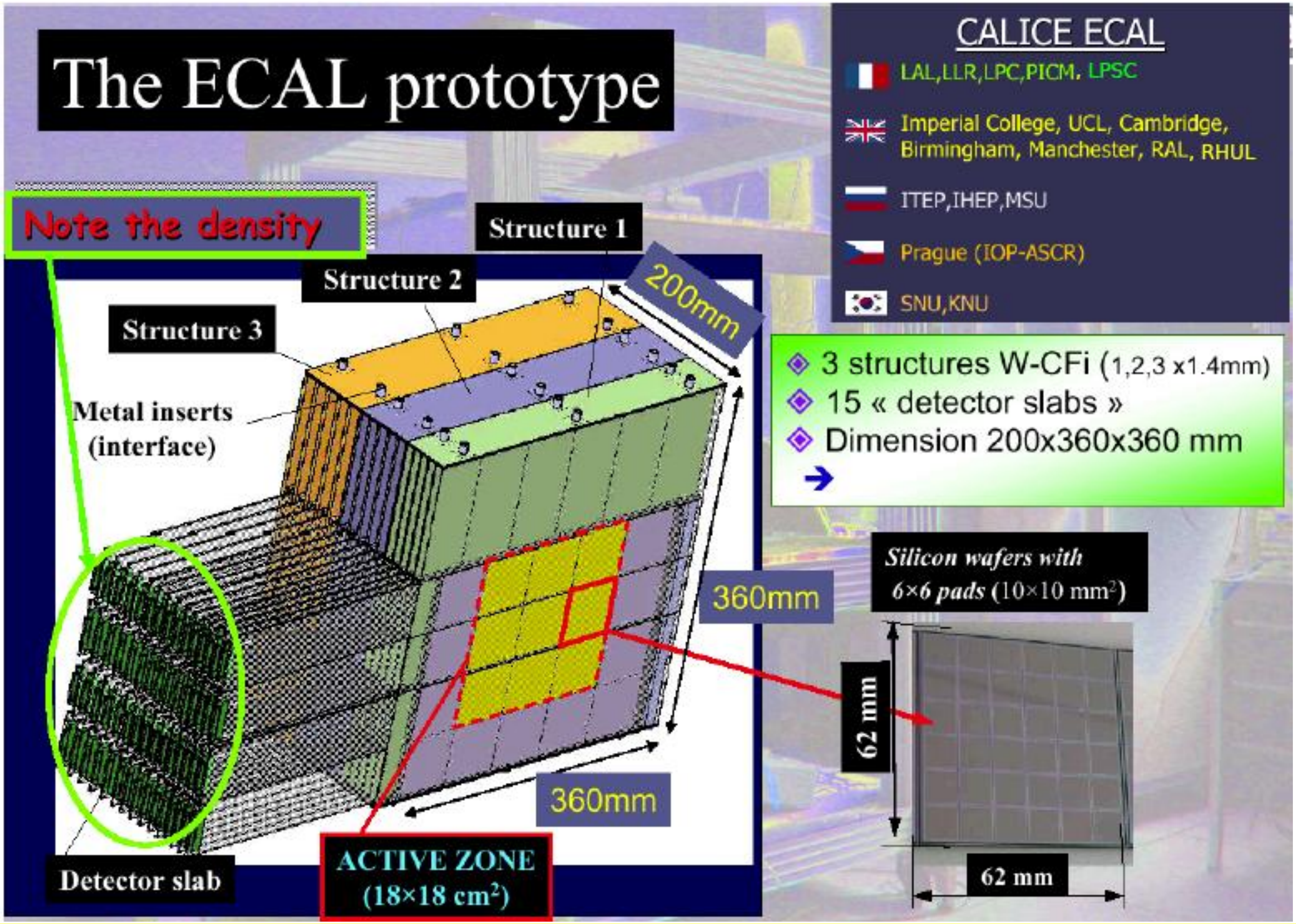
GEANT 4.9.2 used

Summary

- Just presented a few results from CALICE here relating to validation of GEANT4. More in talks in Calorimetry session.
- ECAL and HCAL have complementary merits:
  - ECAL has higher granularity + Tungsten absorber. More effective in discrimination between e/π/p components of shower. But only samples first λ_{int} of the shower.
  - HCAL (+TCMT) detect ~ full shower energy $\Rightarrow$ linearity, resolution studies; tails of showers; sensitive to neutron component.
- In general, GEANT4 performs pretty well, to the 10% level, for most observables, and using most of the physics lists studied.
- A few broad conclusions:
  - LHEP is clearly the least recommendable physics list (useful if you want an outlier).
  - QGSP_BERT (favoured by LHC GPD calorimetry) is a pretty reasonable choice. But in GEANT4.9.3 there is some indication that the FTF-based models perform slightly better. None is perfect.
  - As usual, it depends what you care most about…
  - Other interesting possibilities, such as use of the CHIPS model, are coming along.

Backup slides

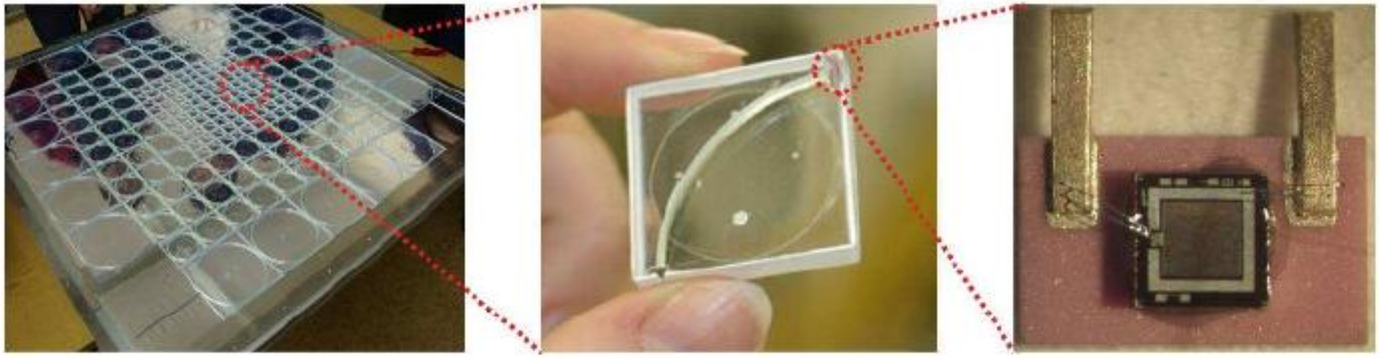
SiW ECAL


The ECAL prototype
Note the density
Structure 1
Structure 2
Structure 3
Metal inserts
(interface)
200mm
360mm
360mm
Detector slab
ACTIVE ZONE
(18×18 cm²)
CALICE ECAL
LAL,LLR,LPC,PICM, LPSC
Imperial College, UCL, Cambridge,
Birmingham, Manchester, RAL, RHUL
ITEP,IHEP,MSU
Prague (IOP-ASCR)
SNU,KNU
3 structures W-CFi (1,2,3 x1.4mm)
15 « detector slabs »
Dimension 200x360x360 mm
Silicon wafers with
6×6 pads (10×10 mm²)
62 mm
62 mm

Analogue HCAL

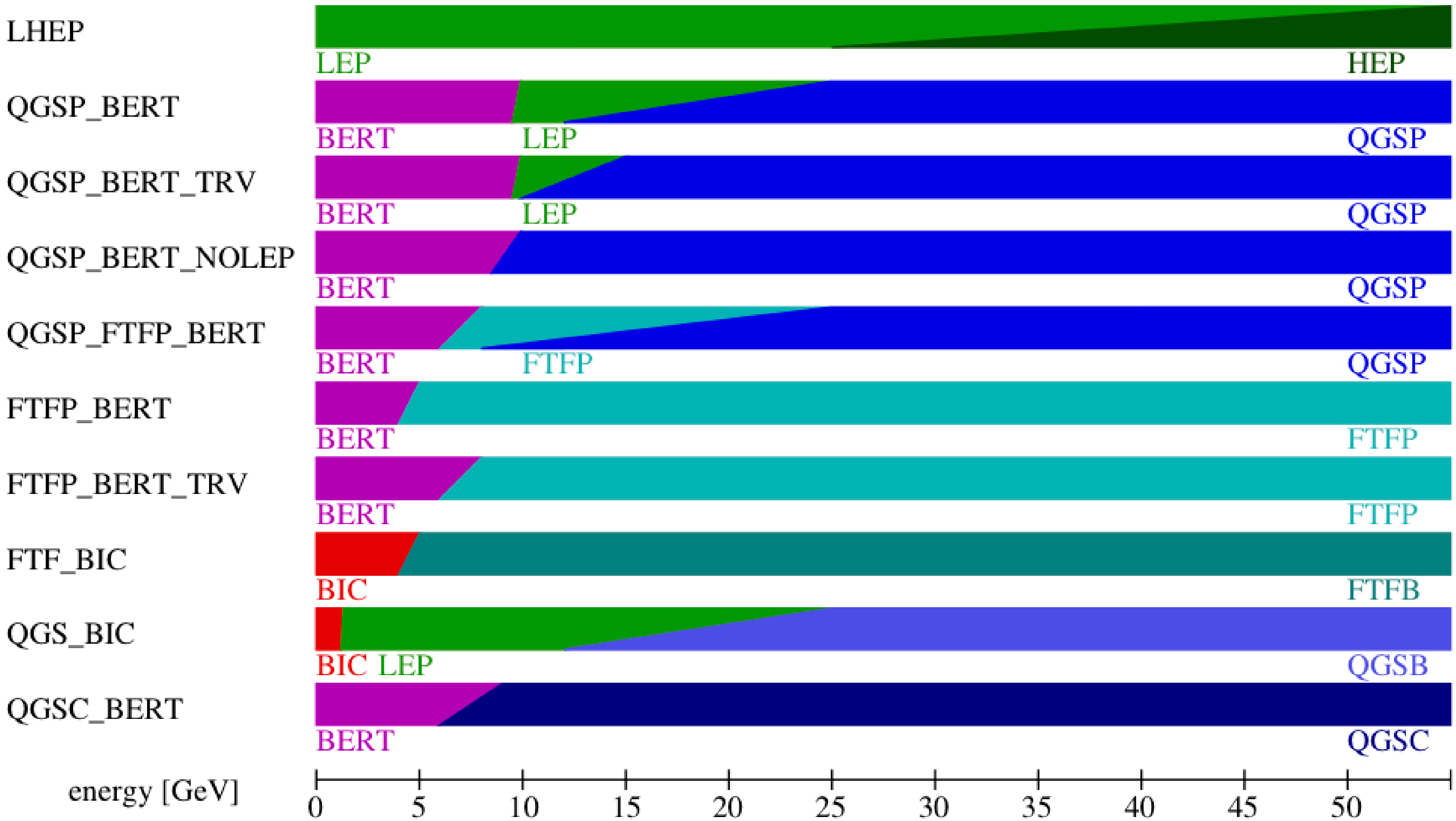
Highly Granular AHCAL Prototype

AHCAL size	$\sim 1\text{m}^3$	channels	7608
materials	Steel -Scintillator	cell size (cm^2)	3x3 to 12x12
layers	38	light yield	~13 pixel/MIP
interaction length	$5.3\lambda_I$	S/N	~10
x-y	scannable		
impact angle	0-30 deg		



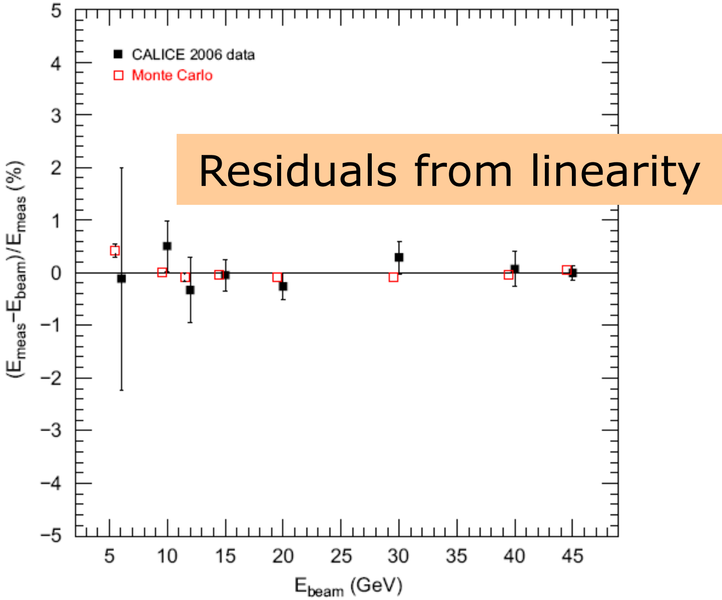
6

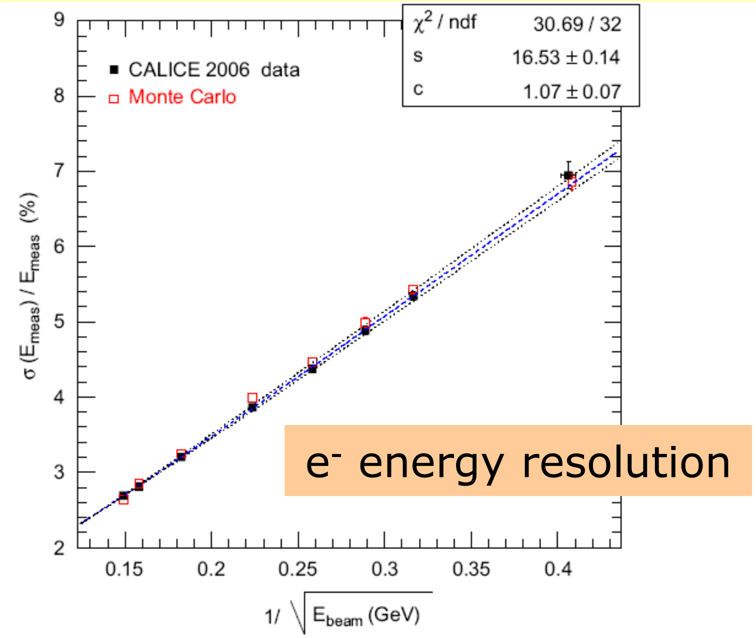
Physics lists in GEANT4.9.3

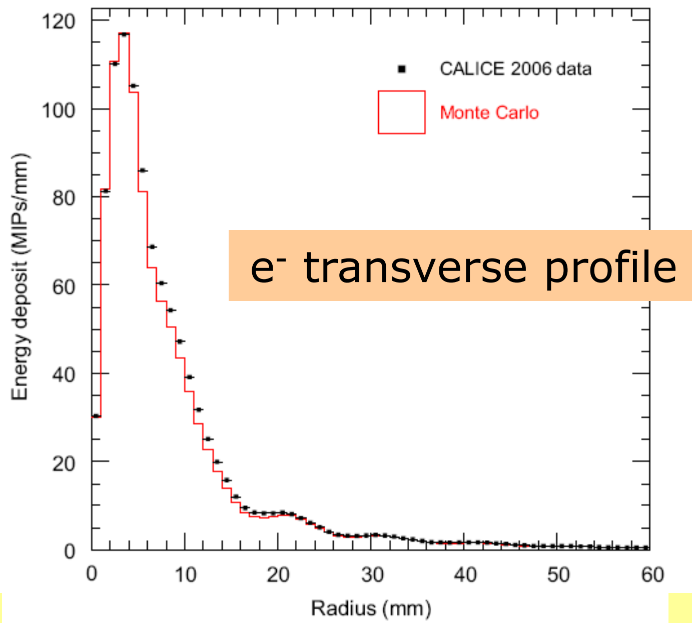


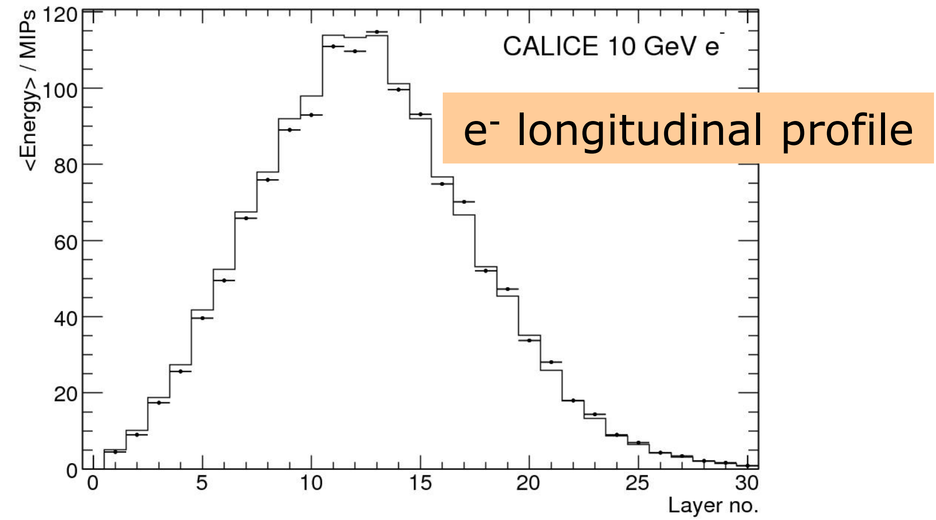
All are hybrids of several models; random selection between alternatives in the transition region in order to smooth behaviour.

Some electron results in ECAL

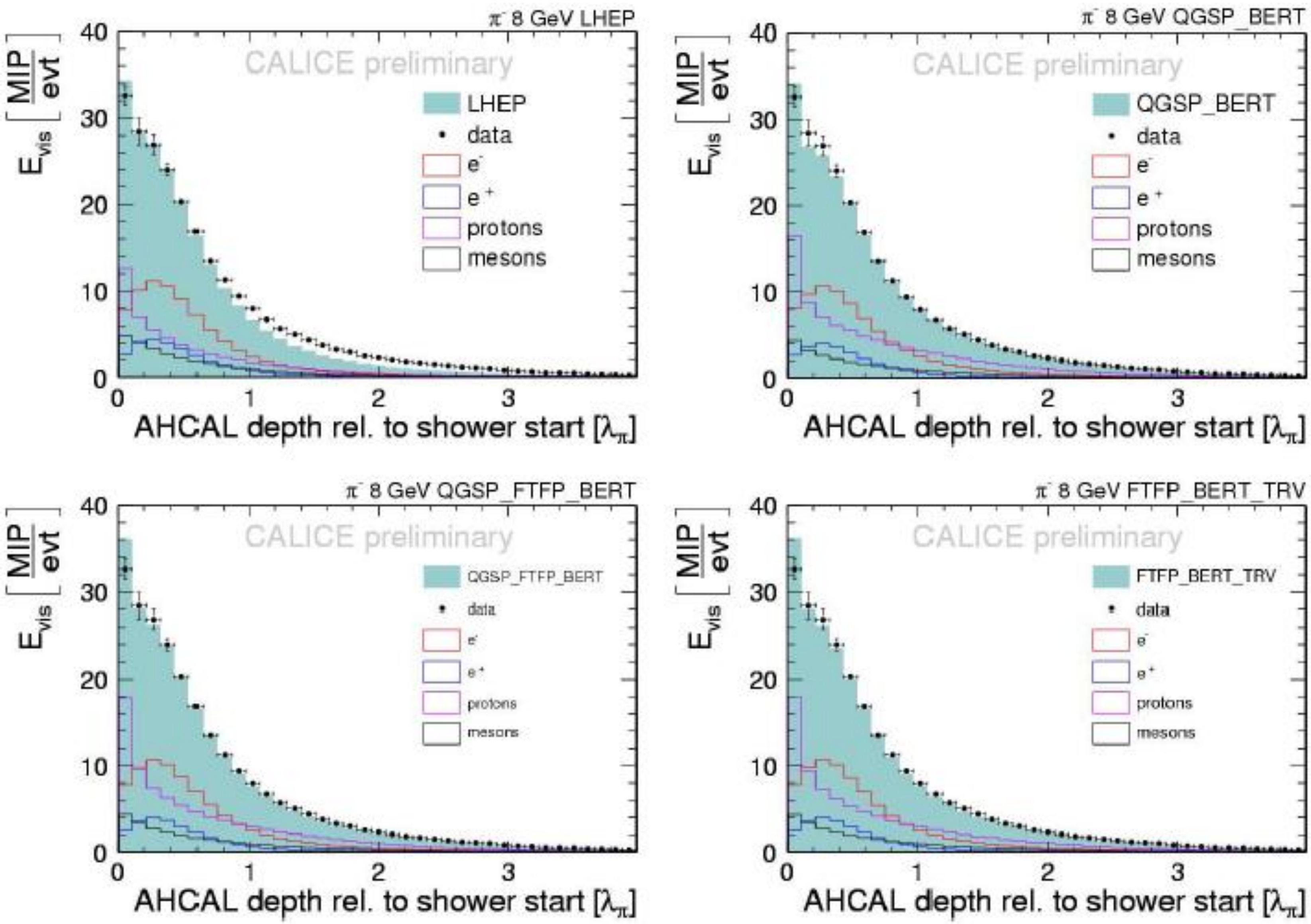








Longitudinal profiles in HCAL (8 GeV)



Longitudinal profiles in HCAL (8 GeV)