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# Hadronic Shower Shape studies in Geant4

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# Outline

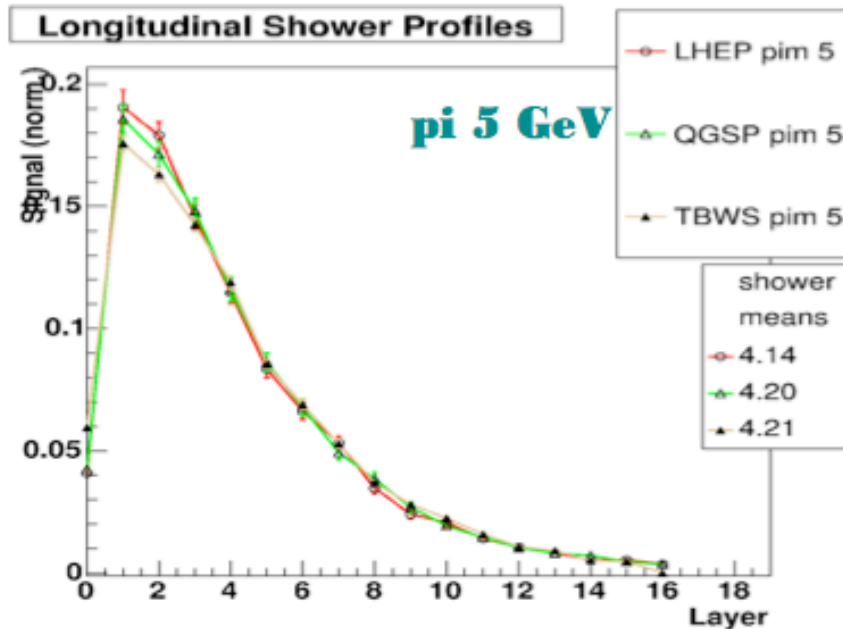
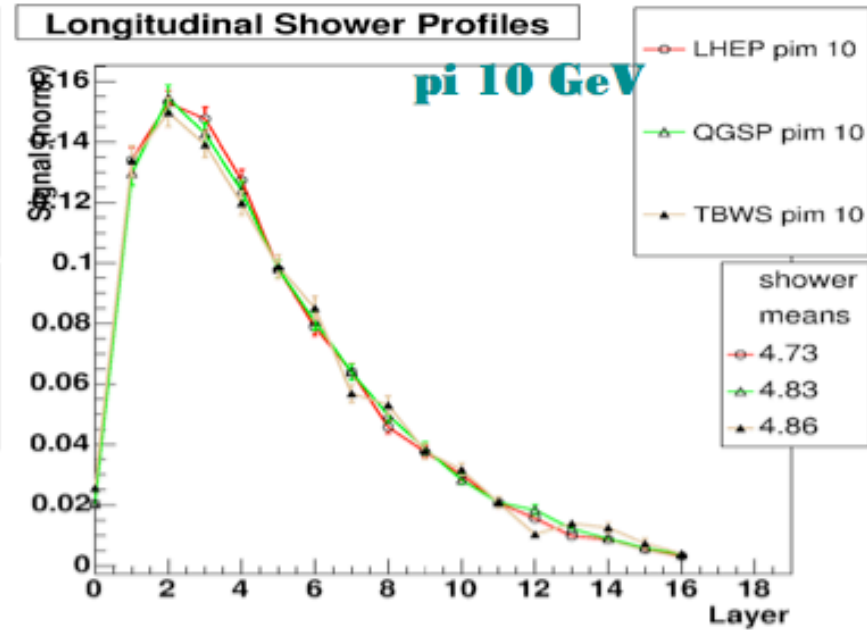
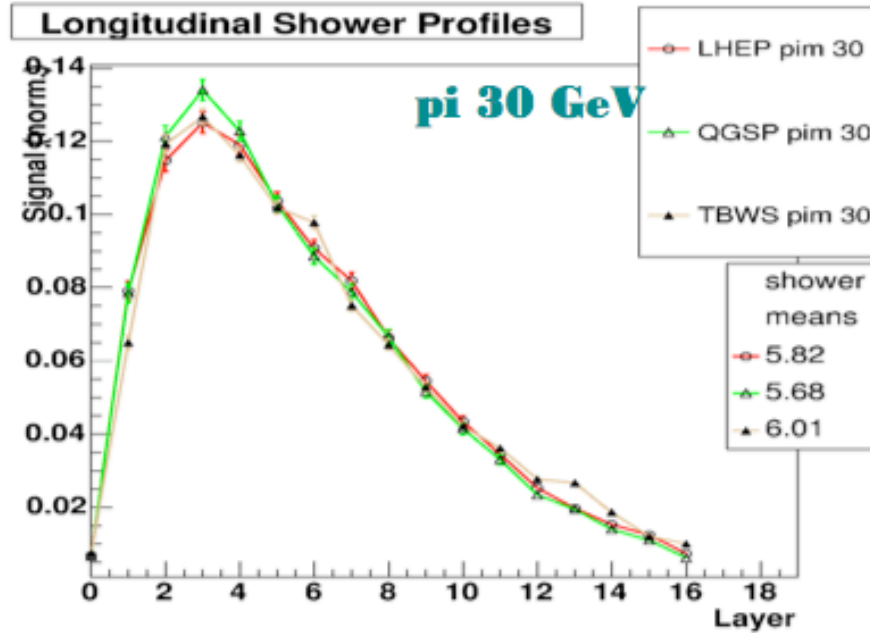
- Motivation
- Strategy
- Simplified calorimeter setup
- Observables
- Results
- Summary
- Outlook

# Motivation

From comparisons between data from calorimeter test-beams of LHC experiments (**ATLAS HEC**, **ATLAS TileCal**, **CMS HCAL**) with Geant4 simulations with **LHEP** and **QGSP** Physics Lists, it has been concluded that:

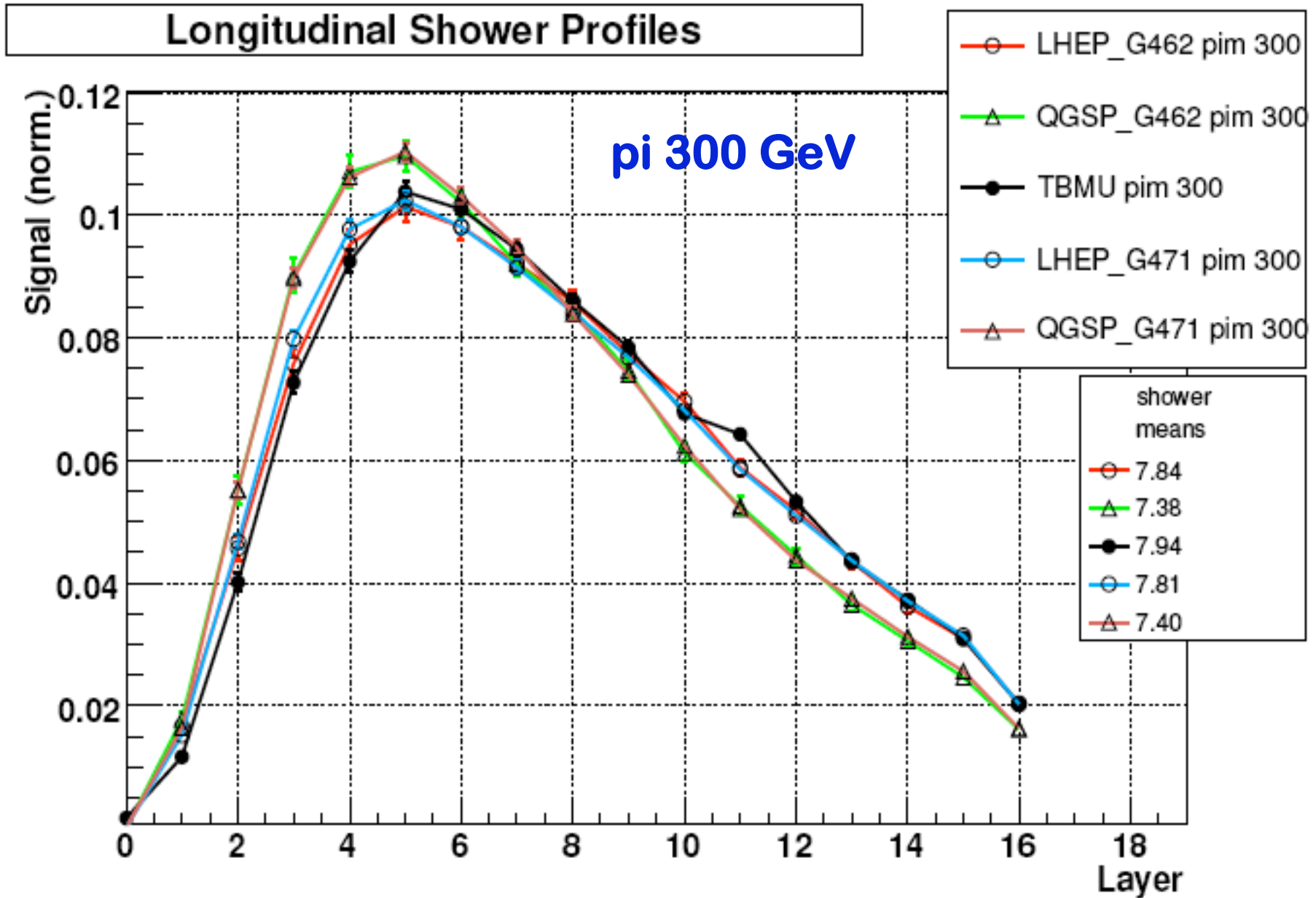
- $\sigma_E/E$  is described well by LHEP and even better by QGSP;
- $e/\pi$  is described very well by LHEP and even better by QGSP;
- **hadronic shower shapes** are **shorter** and **narrower** than data for QGSP, whereas LHEP looks better. QGSP and LHEP are similar at low and intermediate beam energies: good agreement with data for CMS, but not for ATLAS ! ?

# CMS HCAL 2004 test-beam



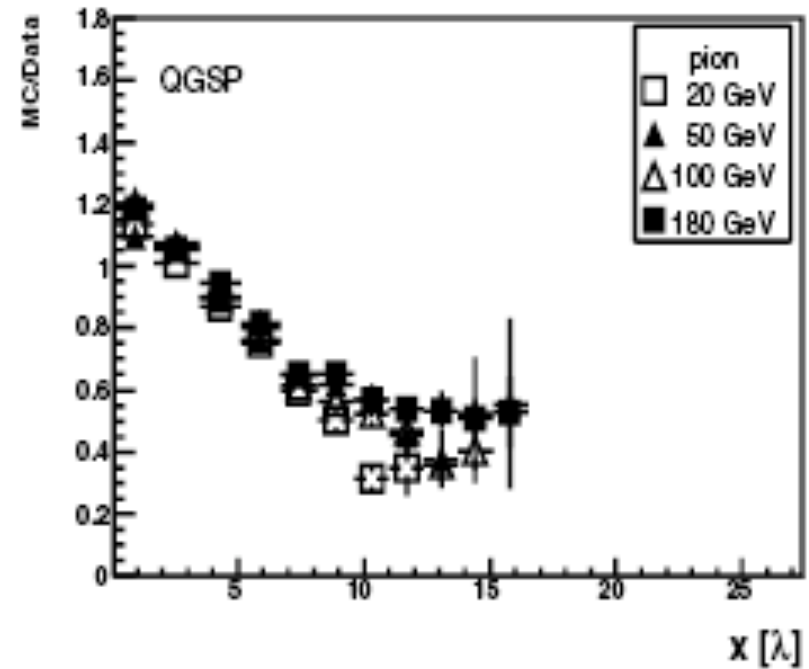
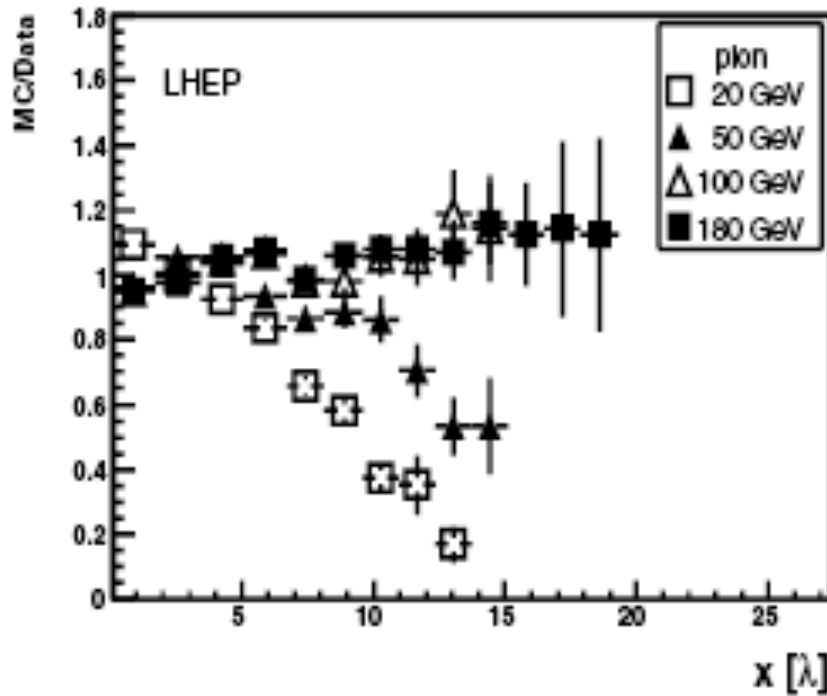
*LHEP and QGSP show good agreement with test beam data at low and intermediate energies*

# CMS HCAL 2004 test-beam



# ATLAS TileCal 2002 test-beam @90° incidence

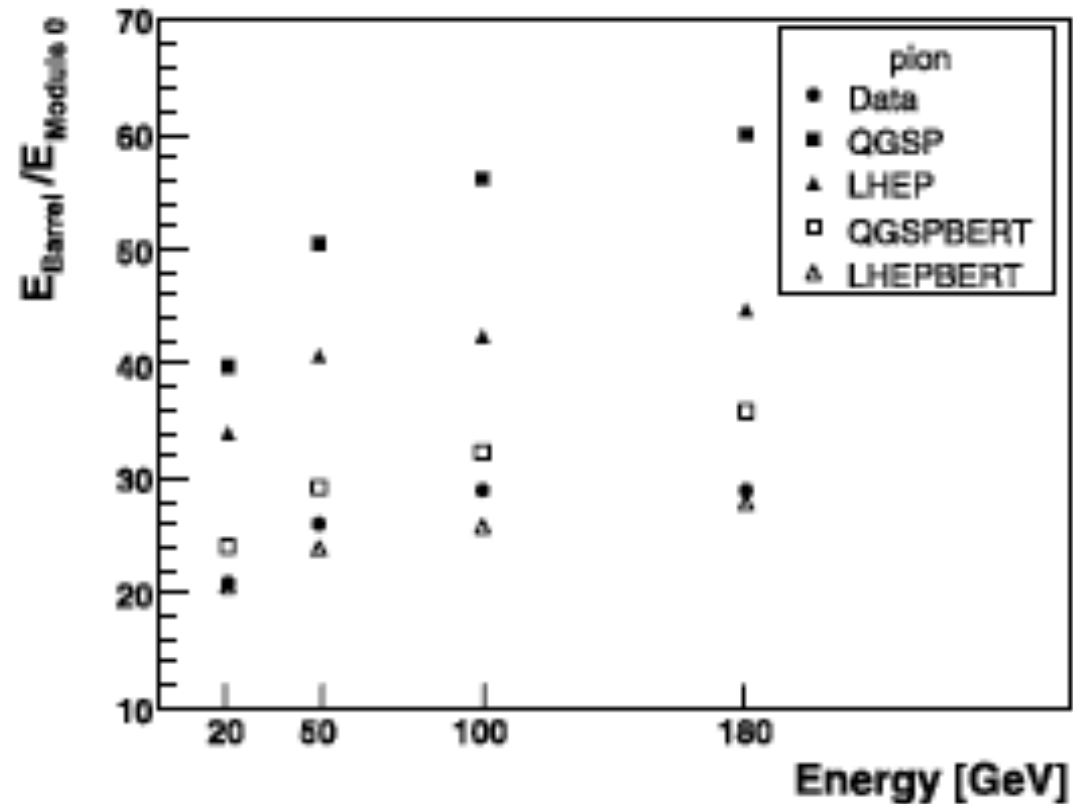
## longitudinal profile



M.Simonyan, Physics Validation meeting 20-Sep-2006

# ATLAS TileCal 2002 test-beam @90° incidence

## lateral profile



M.Simonyan, Physics Validation meeting 20-Sep-2006

# Strategy

The goal is to understand the impact of the various physics processes on the development of hadronic showers, in order to improve the longitudinal (and lateral) shower profiles.

To tackle this complex problem we use two complementary approaches:

1. "microscopic" : study single physics processes, using thin-target data;
2. "macroscopic" : monitor the observables of a sampling calorimeter setup to compare different physics simulations.

This talk is devoted only to the latter approach!  
See Gunter's talk, for the first approach.



## Strategy (cont.)

For the first approach, we start from those physics aspects that we suspect have a major impact on calorimeter observables:

- elastic scattering
- neutron production and transportation
- pion inelastic cross-sections
- multiplicity and spectra.

For the second approach, we start comparing some of the Physics Lists available in Geant4:

- LHEP, QGSP, QGSC, FTFP
- QGSP\_BIC, QGSP\_BERT
- QGSP\_HP, QGSP\_BERT\_HP.

# Simplified Calorimeter setup (1)

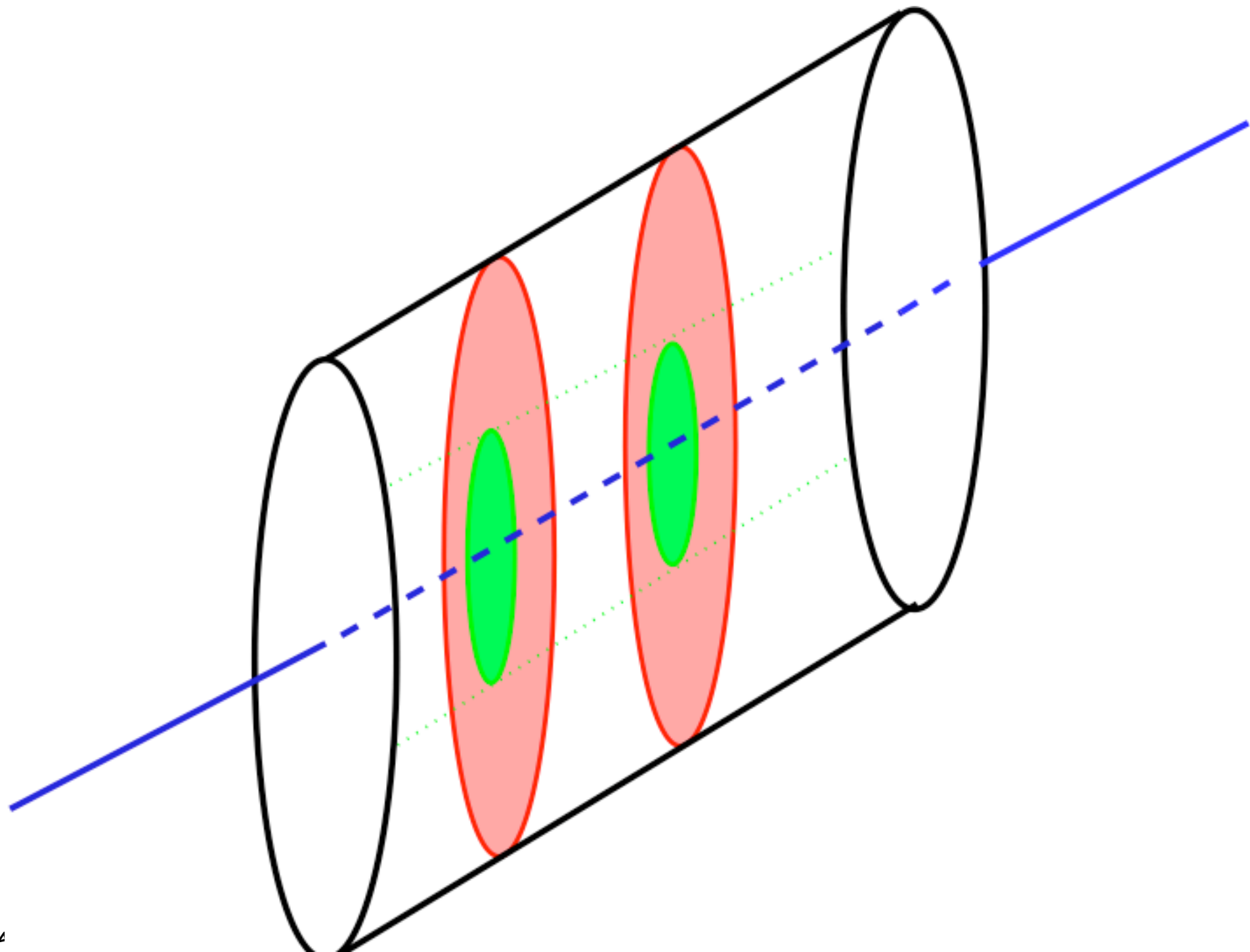
Ultimately, the LHC calorimeter test-beam data will validate any improvement in the hadronic shower shapes.

However, it is useful to compare different physics simulations, between themselves without real data, in simplified calorimeter setups:

- ❑ to avoid to repeat, each time, long and laborious **analyses**, which can be done (currently) only by the experimentalists;
- ❑ to look to many **other variables**, even not measurable, but still interesting;
- ❑ to **decouple pure physics effects from instrumental details** (beam composition, beam profile, complex geometry, noise, cross-talk, digitization, and reconstruction).

## Simplified Calorimeter setup (2)

- It reproduces, in a simplified way, all the LHC calorimeters: Fe-Sci, Cu-Sci, Cu-LAr, W-LAr, Pb-Sci, Pb-LAr, PbWO<sub>4</sub>.
- Beam particle type:  $\pi^+$ ,  $\pi^-$ ,  $k^+$ ,  $k^-$ ,  $k_L^0$ , p, n,  $e^-$ .
- Beam energy: 1, 2, 3, ..., 10, 20, 30, 40, 50, 60, 80, 100, 120, 150, 180, 200, 250, 300 (1000) GeV.
- The calorimeter is a tube. The user can choose:
  - the total thickness of the absorber (in [mm] or  $\lambda$ )
  - the radius of the tube (in [mm] or  $\lambda$ )
  - the thickness of the active layer
  - the number of layers
  - the number and the size (in [mm] or  $\lambda$ ) of the rings for the lateral shower profile.



# "Observables"

- total energy deposit in all active layers
- total energy deposit in the whole calorimeter
- energy deposit in each active layer  
(longitudinal shower profile)
- energy deposit in each ring (i.e. radial bin)  
(lateral shower profile)
- - average number of steps and tracks per event;  
- average track and step length;  
- average number and  $E_{kin}$  of exiting tracks;  
- kinetic energy spectra of tracks entering some active layers;  
each of these is done for different particle types and also for all particle tracks;  
- contributions to the visible energy and shower shapes for different particle types.

# Configurations used

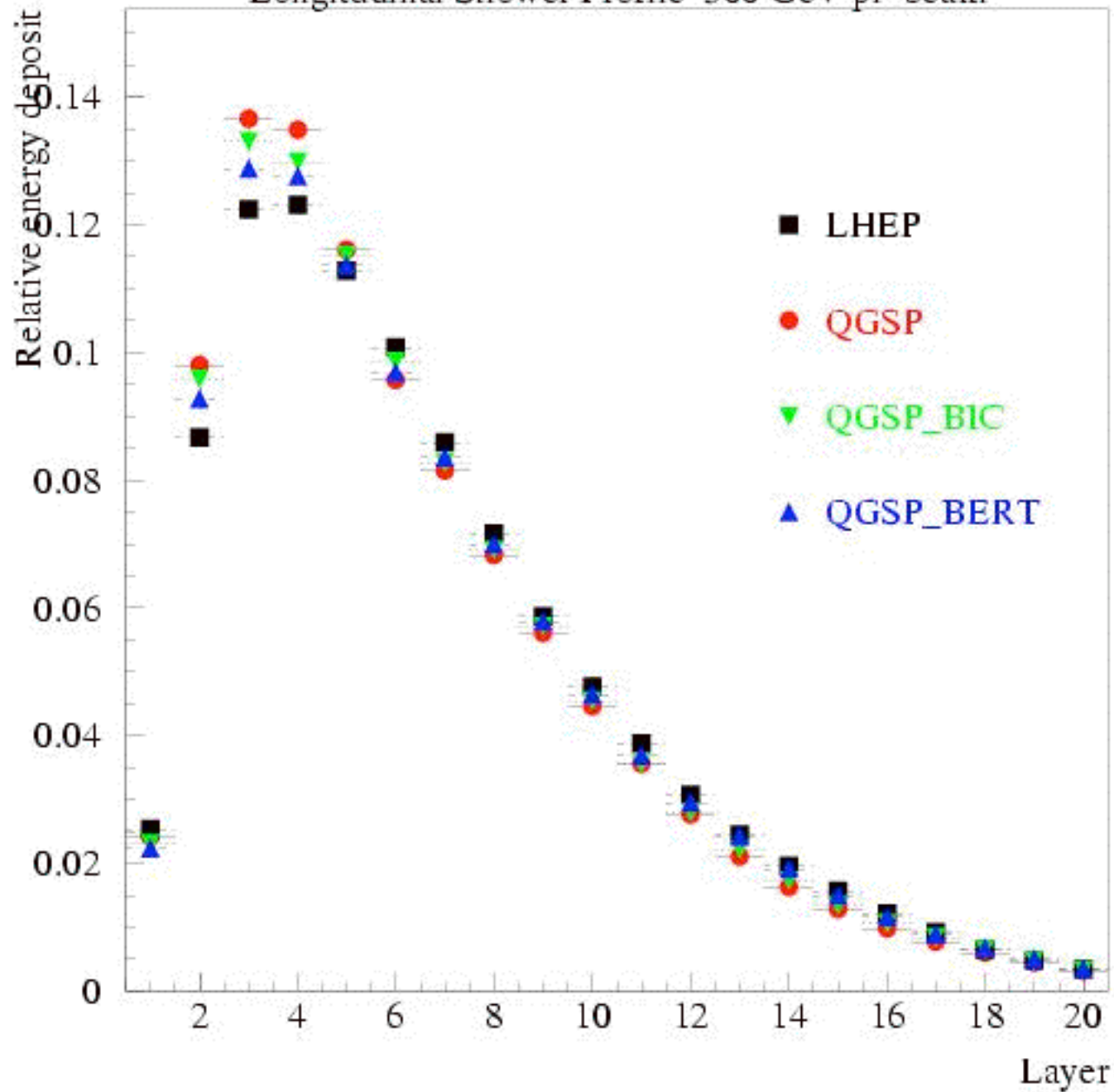
- Geant4 8.0.ref04 (so, rough hadronic elastic!)
- default production range cut: 0.7 mm  
(but we made some tests also with 10  $\mu\text{m}$ )
- Primary beam particle: 30, 100, 300 GeV  $\pi^-$
- Main setup: simplified ATLAS HEC  
60 layers Cu (25 mm) - LAr (8.5 mm)  
(about 10 lambda), with 20 readout layers.

NB) We studied also the simplified CMS HCAL  
25 layers Cu (60 mm) - Sci (4 mm)  
but it is too sensitive to the elastic scattering...

Beam energy 300 GeV

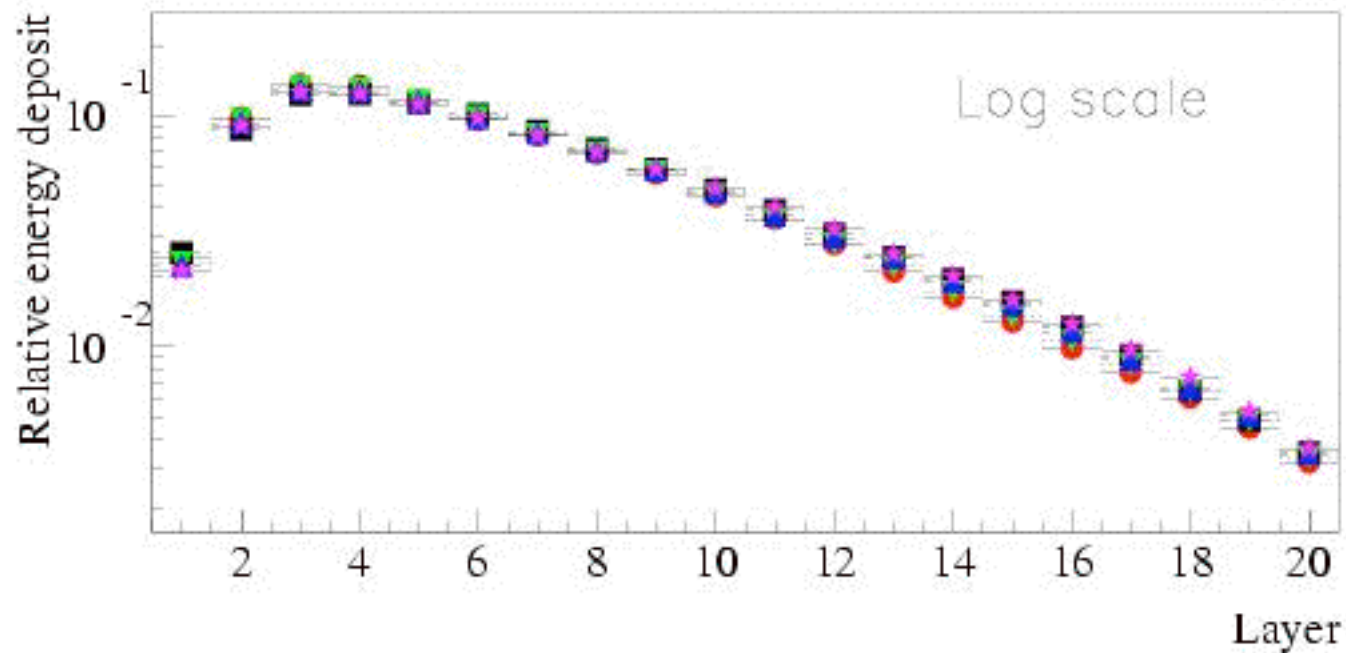
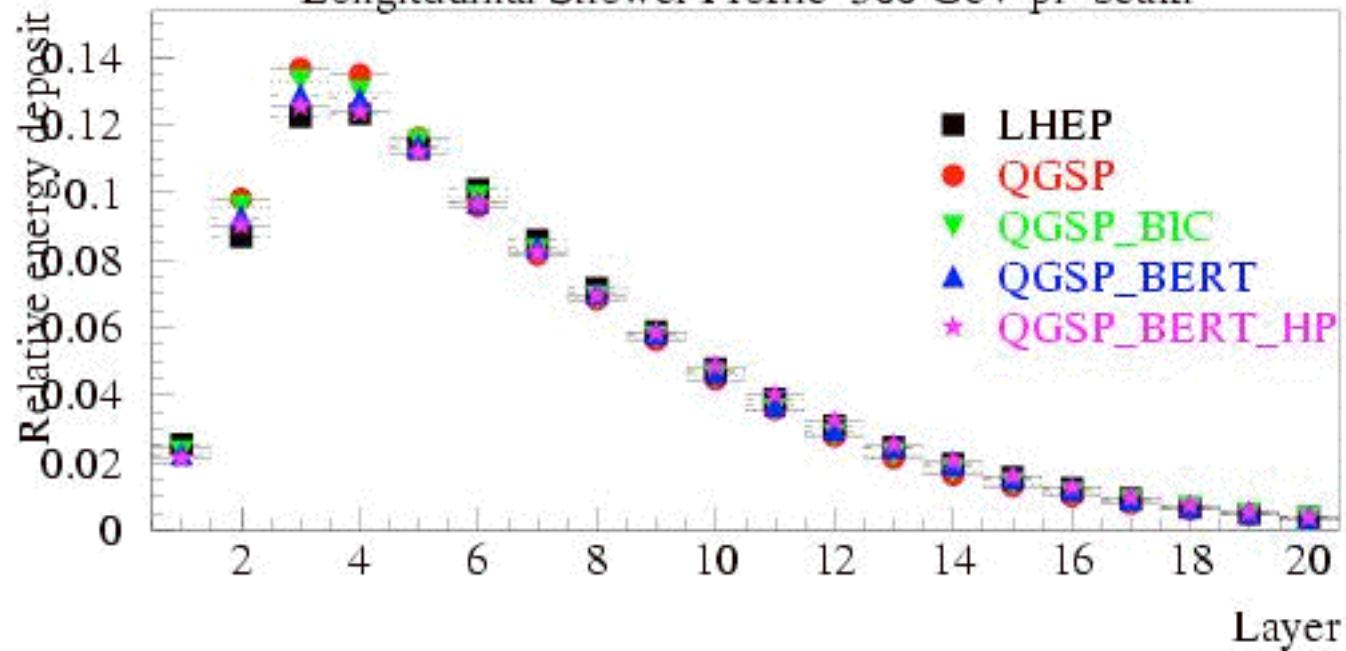
Normalized shower shapes  
per Physics List

Longitudinal Shower Profile 300 GeV pi- beam

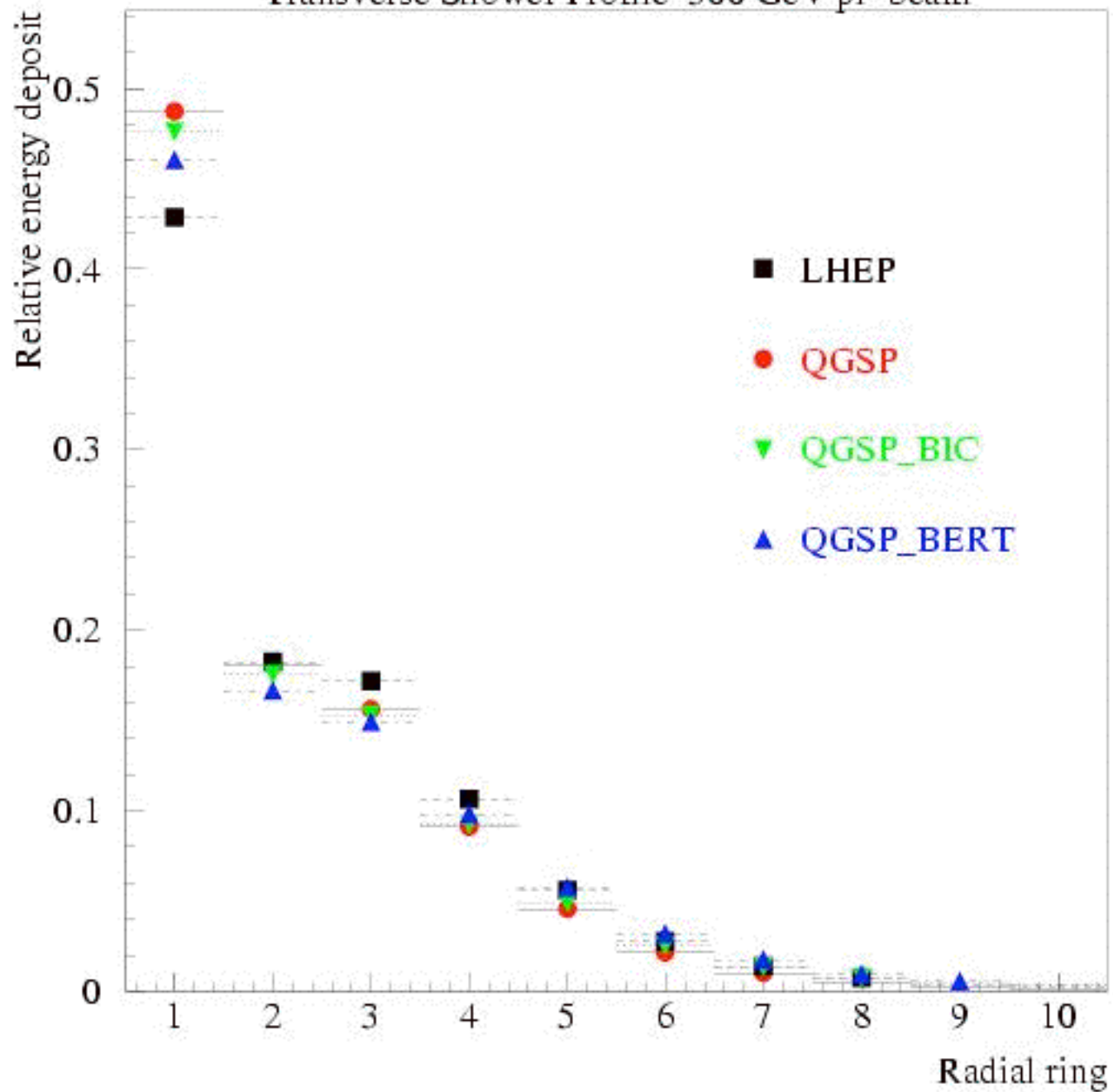




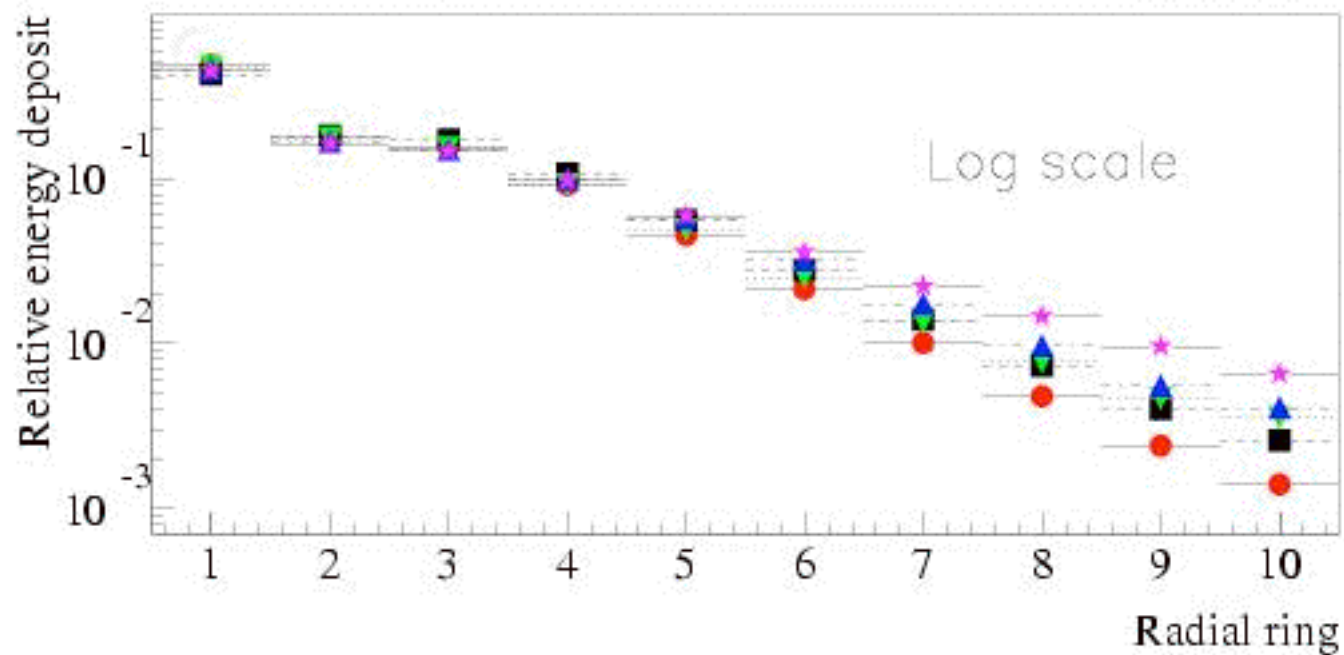
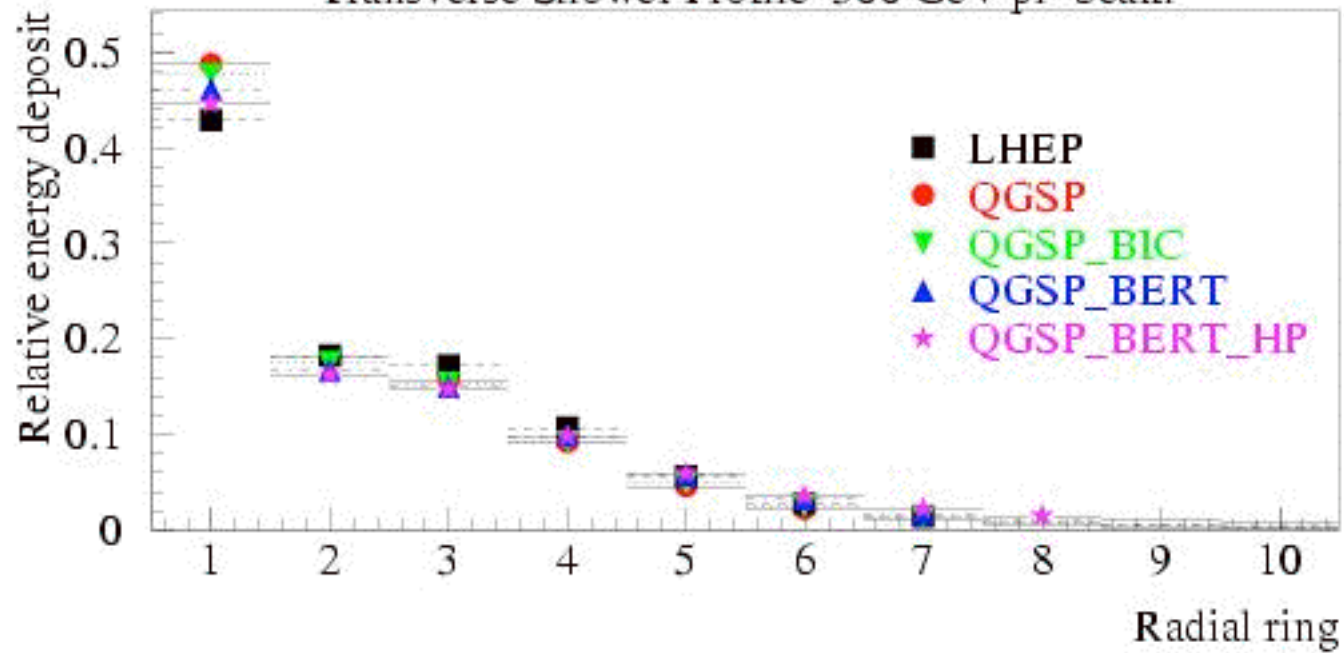
Longitudinal Shower Profile 300 GeV pi- beam



Transverse Shower Profile 300 GeV pi- beam



Transverse Shower Profile 300 GeV pi- beam



## Some observations

- For both the longitudinal and lateral profiles:  
 $QGSP \leq QGSP\_BIC \leq QGSP\_BERT \leq QGSP\_BERT\_HP$
- The effect of **\_HP** is mainly outside the “bulk” of the shower (in the longitudinal and lateral **tails**).
- **LHEP** produces the longest showers at 100 and 300 GeV; at 30 GeV it is the shortest (but close to QGSP); for the lateral profile, LHEP is always wider than QGSP and QGSP\_BIC, and narrower than QGSP\_BERT\_HP; with respect QGSP\_BERT, it is slightly narrower at 30 GeV, and slightly wider at 100 and 300 GeV.
- **QGSC** and **FTFP** are very similar to QGSP  
(not shown here!)

$$E_{vis} , \sigma_E/E , e/\pi$$

In these comparisons between different Geant4 Physics Lists, we concentrate only on the hadronic shower shapes, but of course there are other important observables to consider, such as the visible energy, energy resolution, and  $e/\pi$ .  
Briefly:

- For the visible energy

$$\text{LHEP} \leq \text{QGSP} \leq \text{QGSP\_BIC} \leq \text{QGSP\_BERT} \\ \leq \text{QGSP\_BERT\_HP}$$

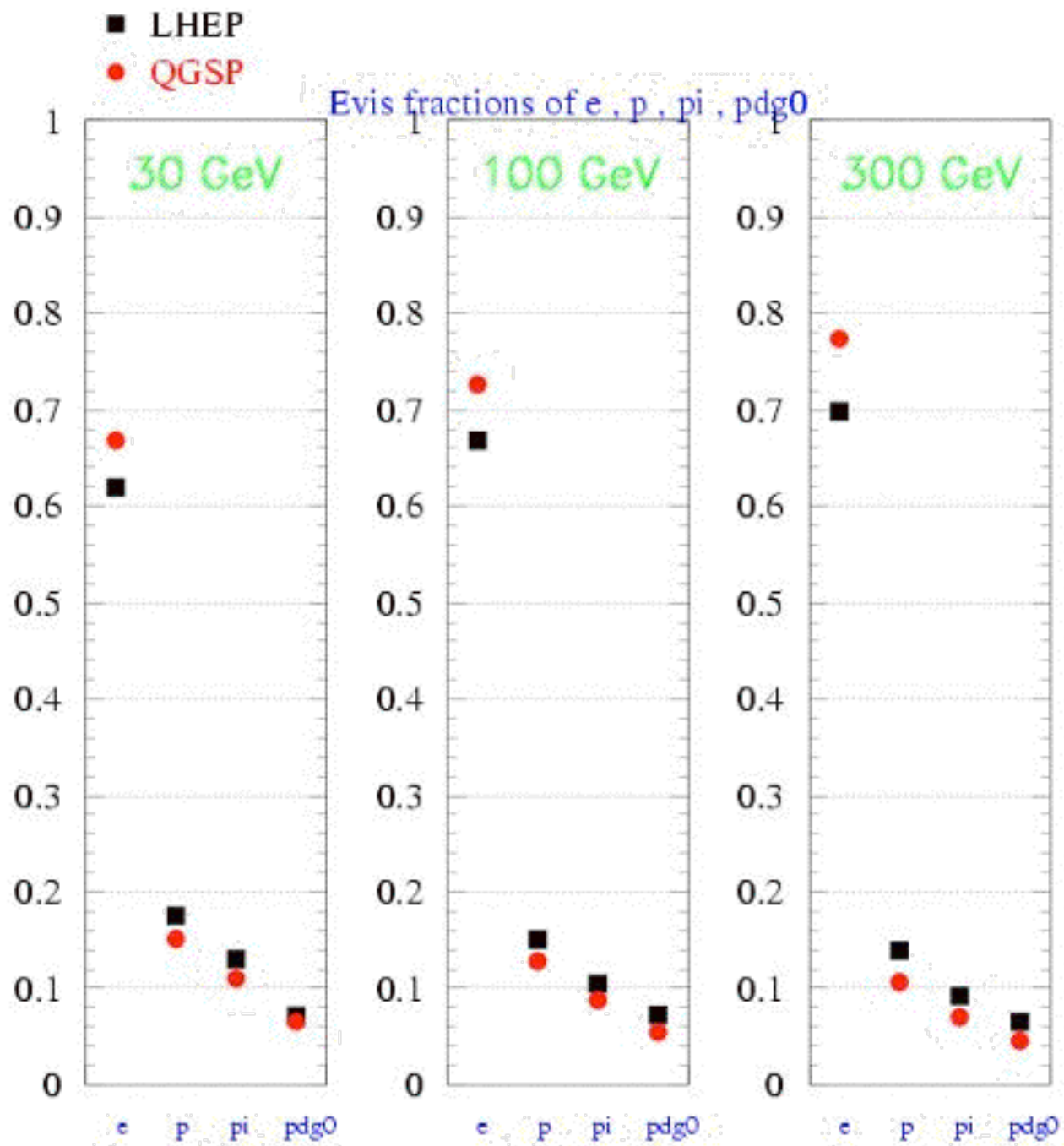
- For the the energy resolution and the ratio  $e/\pi$

$$\text{LHEP} \geq \text{QGSP} \geq \text{QGSP\_BIC} \geq \text{QGSP\_BERT} \\ \geq \text{QGSP\_BERT\_HP}$$

# Particle contributions

- We want to study how much different particle types contribute to the visible energy, and which is shower shape (longitudinal and transverse) for each of them.
  
  - We consider the following particle types
    1.  $e^-/e^+$
    2.  $p/pbar$
    3.  $\pi^+/\pi^-$
    4. nuclei (PDG code = 0)
- NB) The contribution of kaons and muons is negligible (<1%).

We consider always a primary beam of  $\pi^-$ .

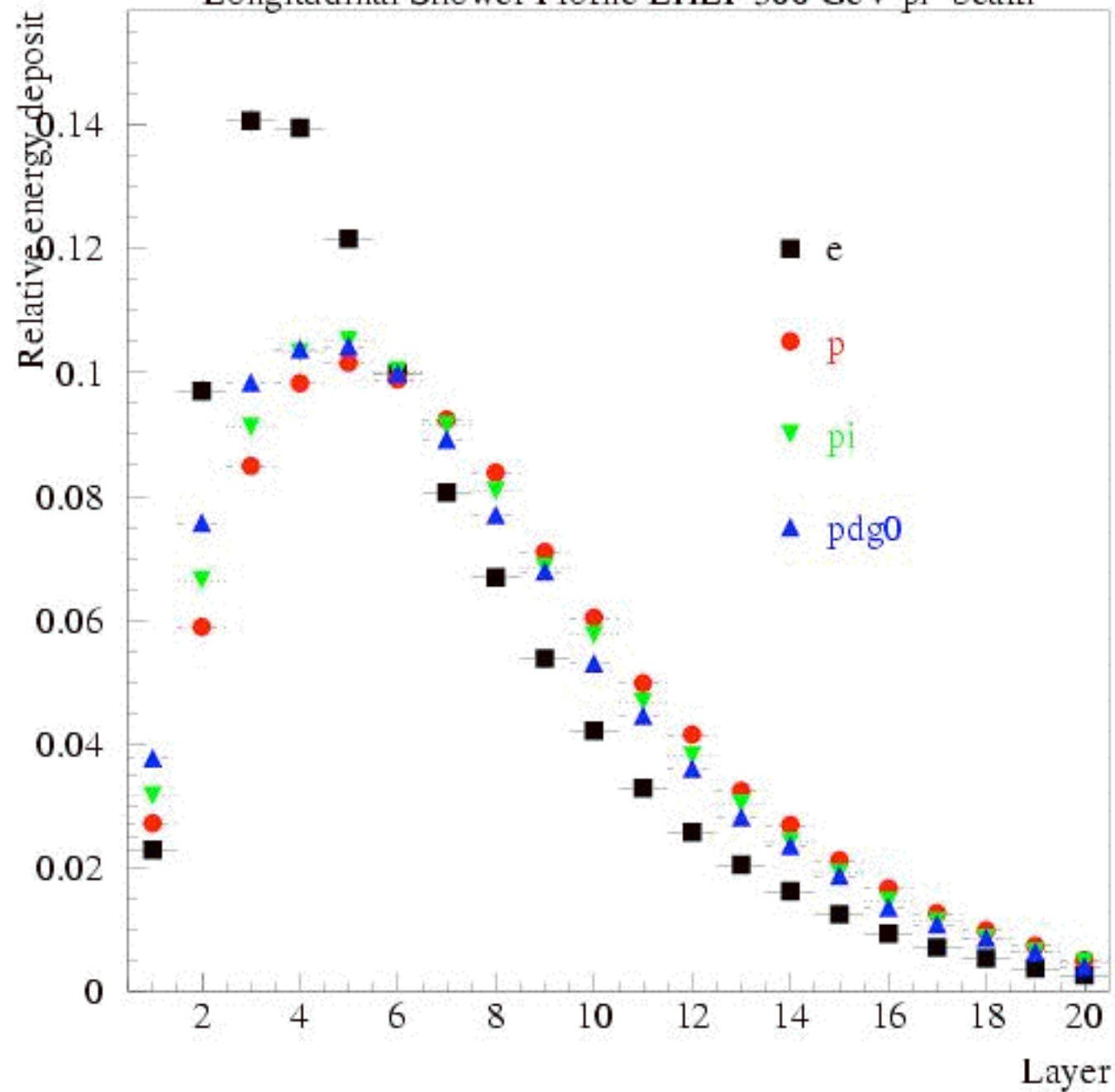


Beam energy 300 GeV

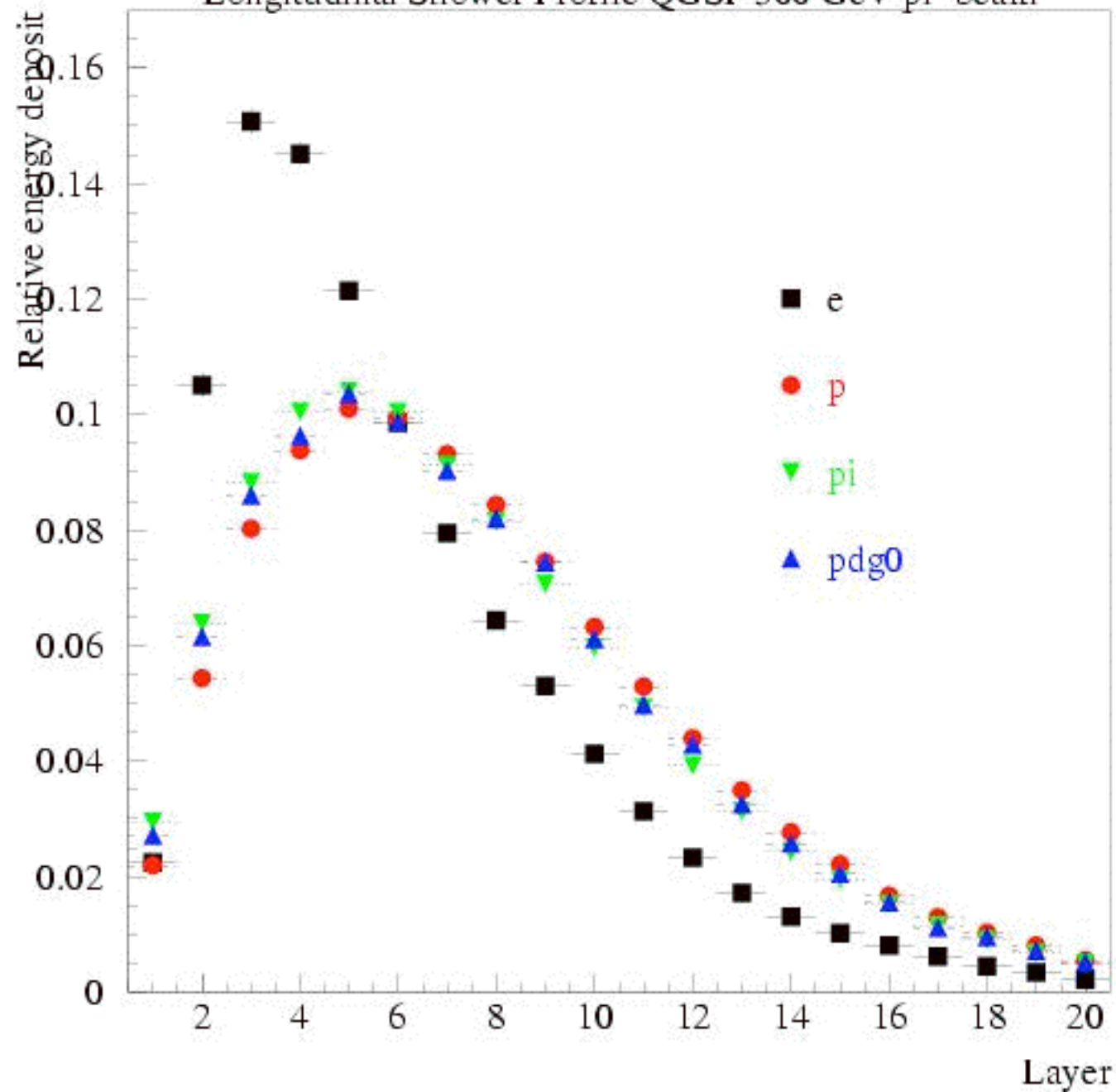
Normalized shower shapes  
per Particle type



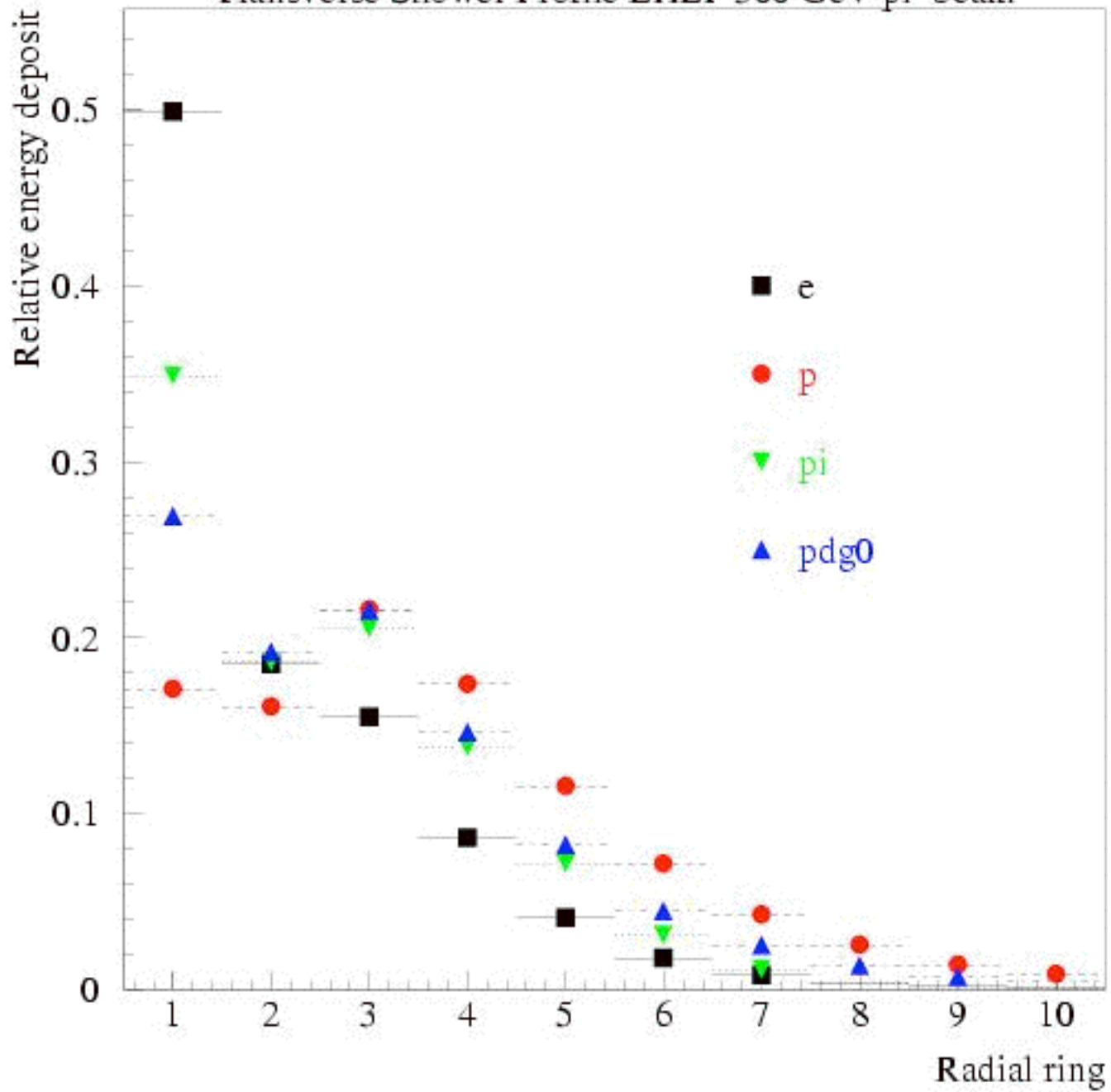
Longitudinal Shower Profile LHEP 300 GeV pi- beam



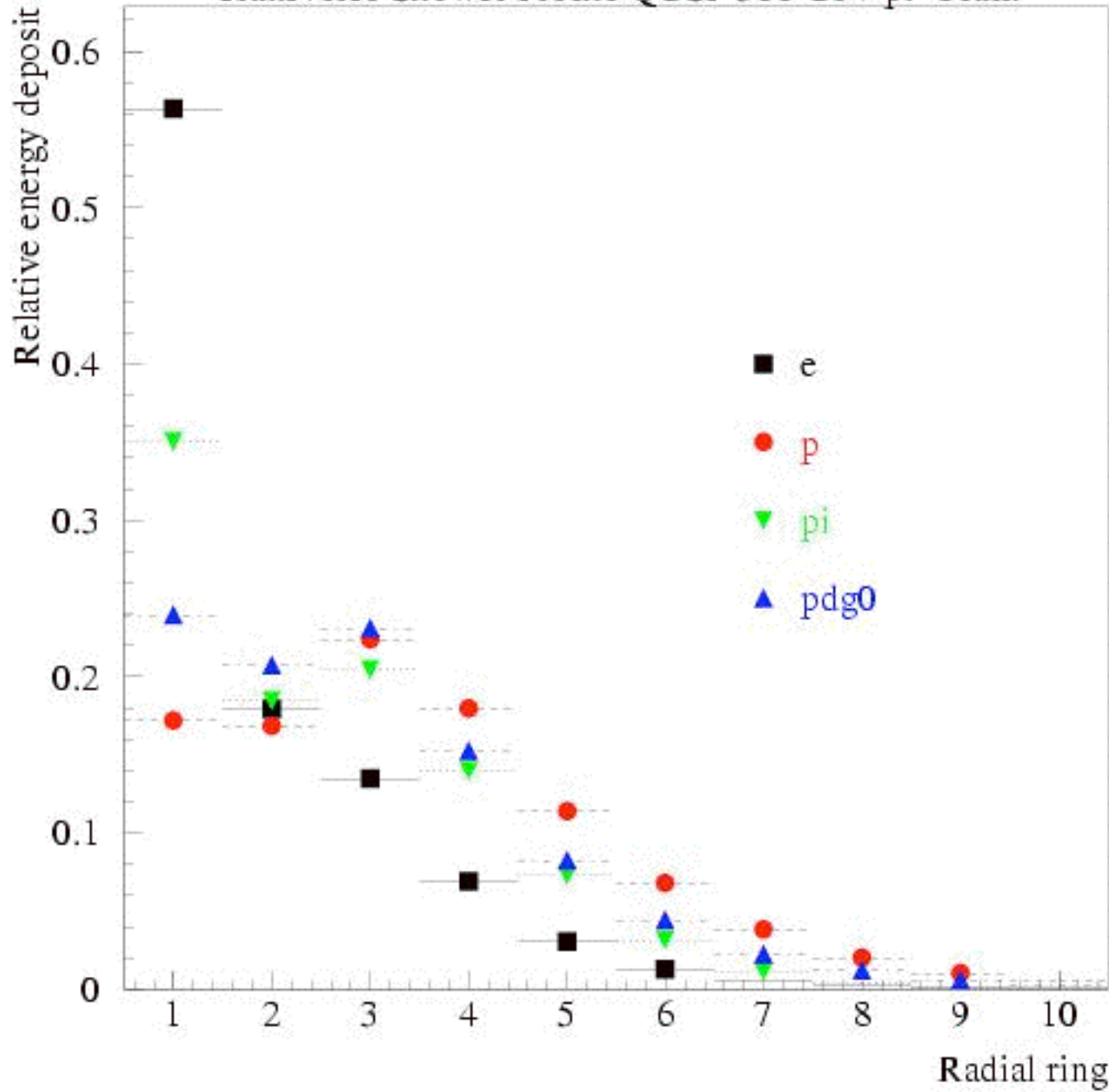
Longitudinal Shower Profile QGSP 300 GeV pi- beam



Transverse Shower Profile LHEP 300 GeV pi- beam



Transverse Shower Profile QGSP 300 GeV pi- beam



## Some observations

- The relative contribution to the visible energy per particle type is:  $e \gg p > \pi > \text{pdg0}$   
and the electron dominance grows as the beam energy increases.
- For both longitudinal and lateral shower shapes  
 $e \ll \pi < \text{pdg0} < p$
- Comparing QGSP with respect to LHEP :
  - QGSP has larger electron contribution, especially for higher beam energies;
  - QGSP has shorter and narrower electron shape;
  - QGSP has similar shapes for the others (only slightly narrower, and slightly longer at 30 and 300 GeV, for protons and pdg0).

# Number of tracks

Let's compare the average number of tracks per event of LHEP with respect QGSP:

	30 GeV	100 GeV	300 GeV
# EM	-10%	-11%	-12%
# $\pi^{+/-/0}$	+16%	+19%	+24%
# p	+12%	+17%	+23%
# n	+12%	+17%	+22%
# pdg0	+13%	+18%	+24%

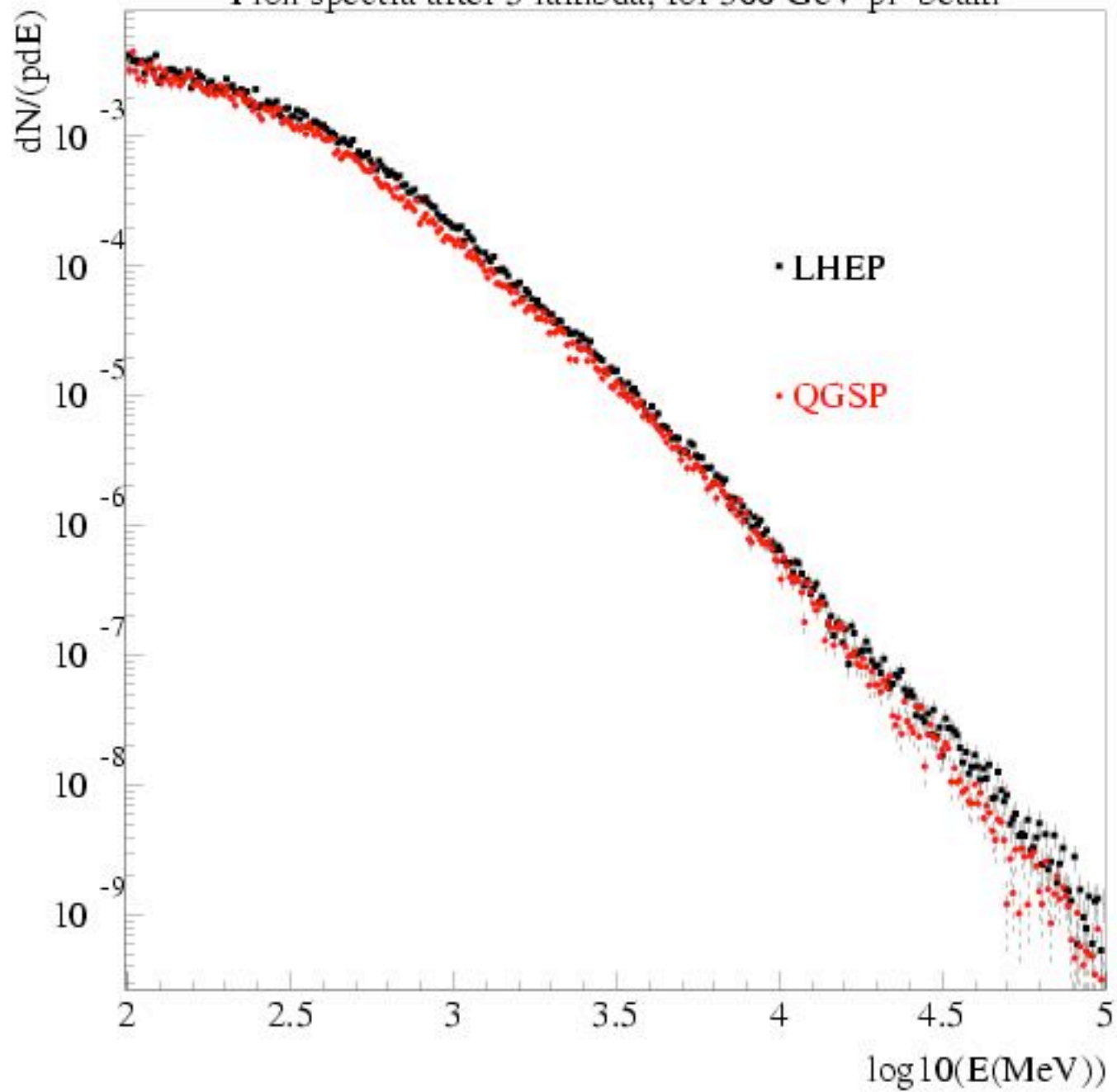
The ratio  $\pi^0/\pi$  is the same for LHEP and QGSP!  
Consistent with results with 1 km production cut...

Let's look at the particle spectra...

Beam energy 300 GeV

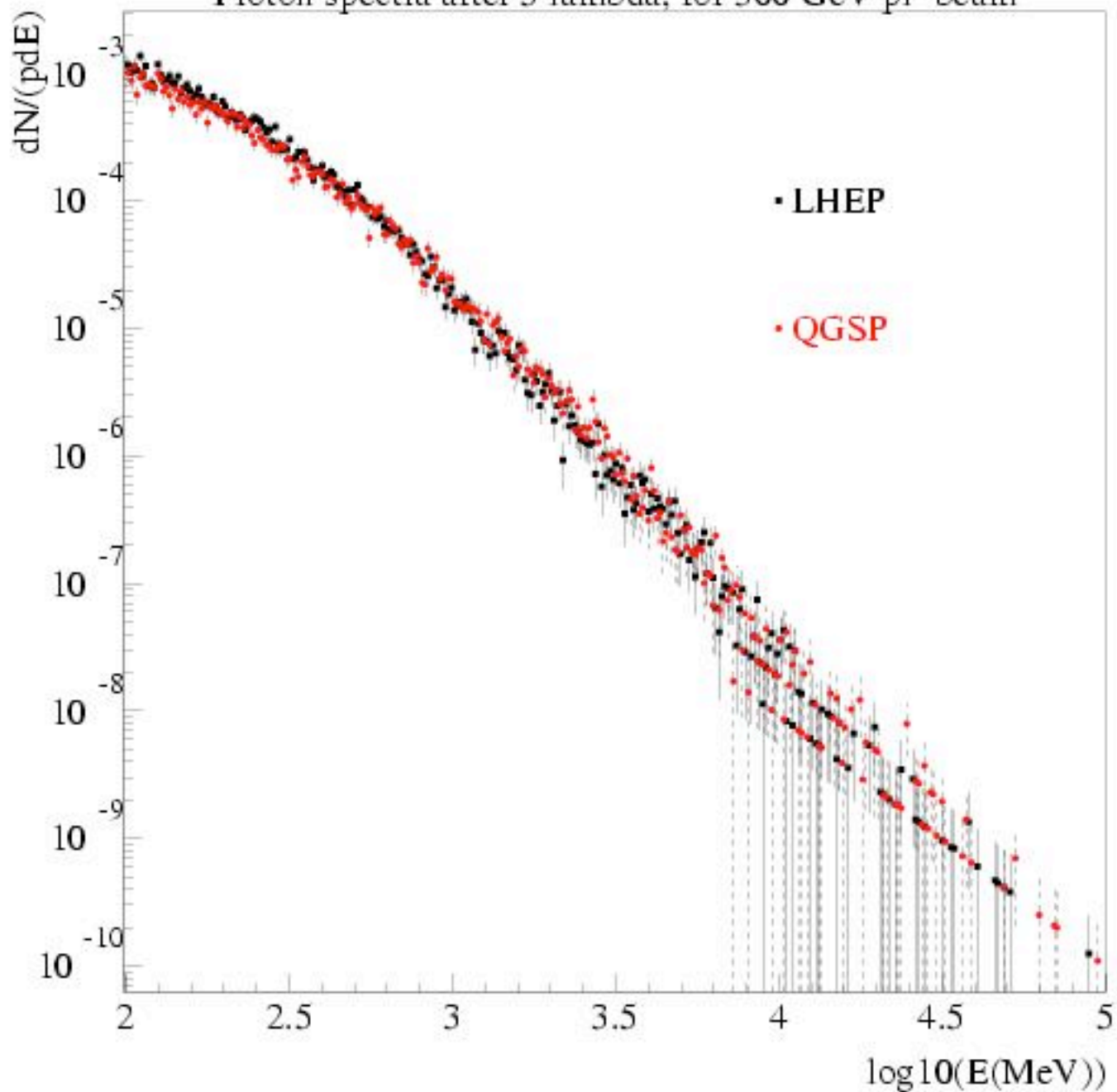
Particle ( $\pi^\pm$ , p, n) spectra  
after 5  $\lambda$

Pion spectra after 5 lambda, for 300 GeV pi- beam

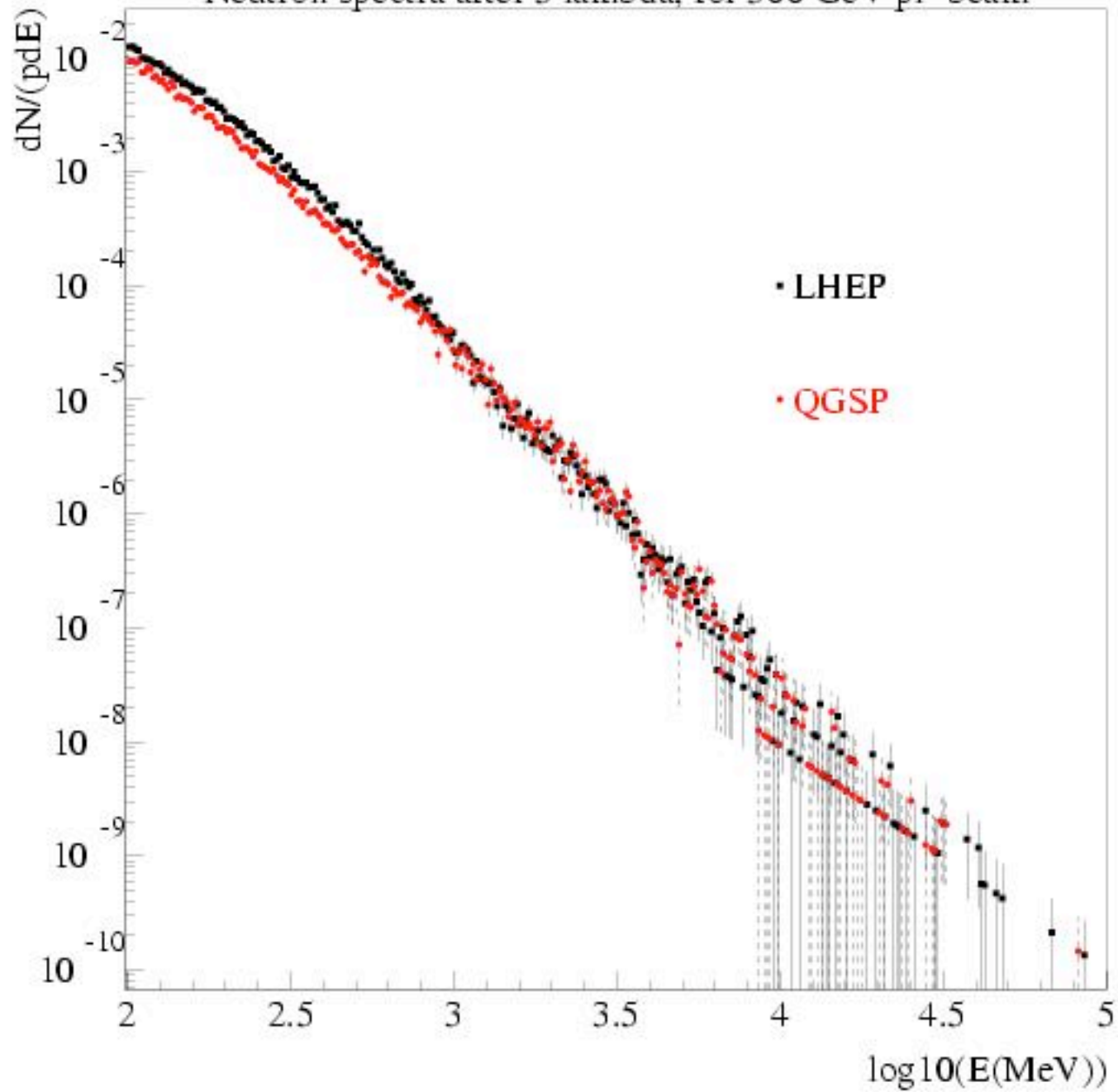




Proton spectra after 5 lambda, for 300 GeV pi- beam



Neutron spectra after 5 lambda, for 300 GeV pi- beam



# $\eta$ , $\eta'$ , $\rho^0$ production

More than 70% of  $\eta$  decays are neutral;

Almost all  $\rho^0$  decays into  $\pi^+ \pi^-$  ;

About than 85% of  $\eta'$  decays are charged.

If QGS over-produces  $\eta$  or under-produces  $\rho^0, \eta'$   
then the em component would be overestimated...

Number of tracks produced in 5000 events of  
300 GeV  $\pi^-$  on Cu-LAr calorimeter:

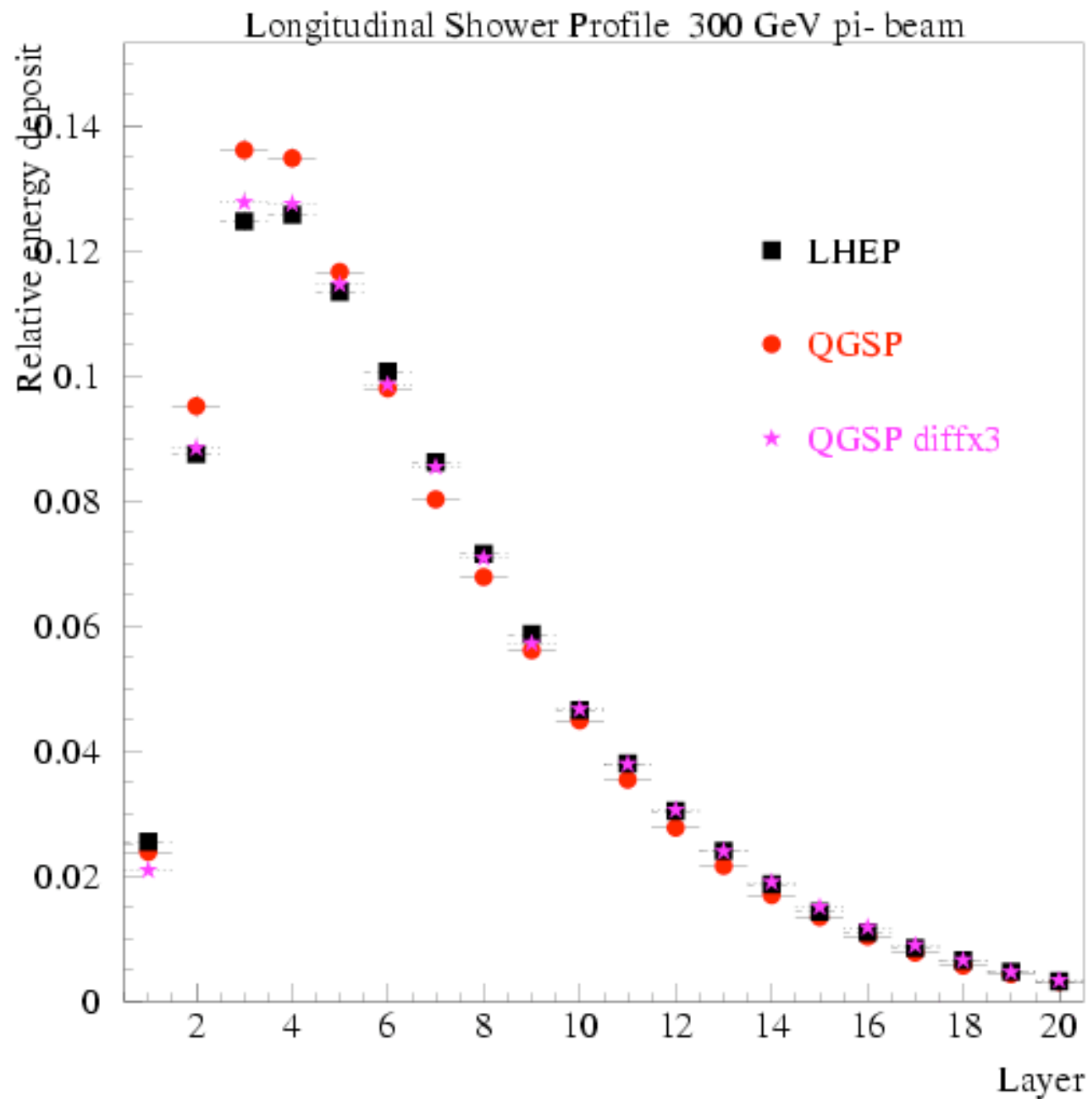
	$\eta$	$\eta'$	$\rho^0$
LHEP	36	15	2
QGSP	16630	5579	1763
QGSC	13545	4721	1522
QGSP_BIC	17634	5592	1759
QGSP_BERT	16265	5598	1831

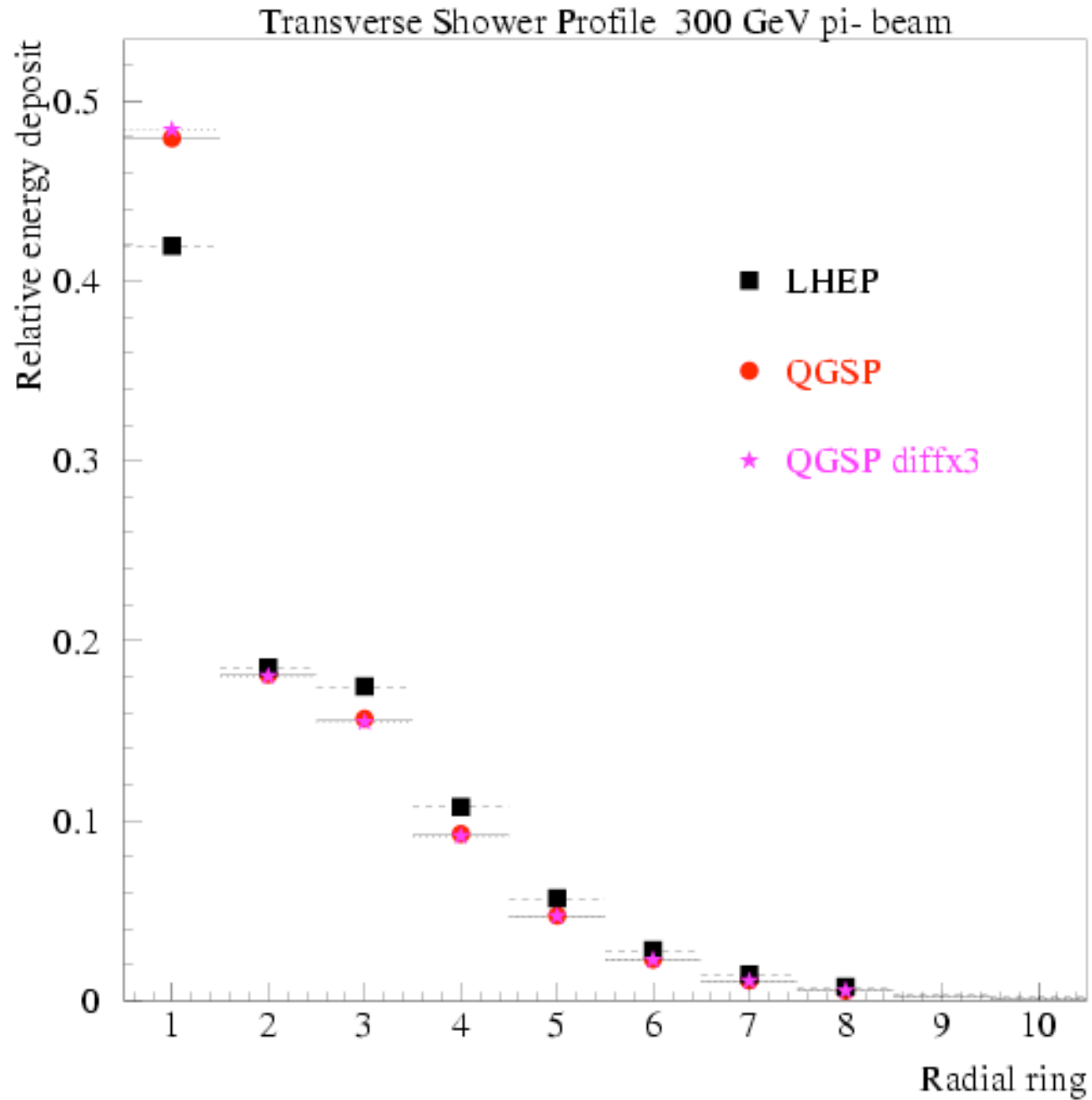
# Diffraction

Some of the rapidity distributions data (e.g. Whitmore) that we use for benchmarking Geant4 does not include the diffractive events, so it is possible that such component is not properly tested. We have tried to change by hand the relative fraction of diffractive events, without modifying the model:

`geant4/source/processes/hadronic/models/parton_string/qgsm/src/G4QGSParticipants.cc`

By increasing the diffractive component the longitudinal shower profile gets longer and a bit narrower.





# Summary

We have compared the hadronic showers for some Geant4 Physics Lists. Although we do not have yet a complete understanding of the differences, some useful information have been collected:

- adding **cascade models** (Bertini, Binary) the hadronic showers get a bit **longer** and **wider**;
- adding a precise transportation of low-energy neutrons (**HP**) does not affect the bulk of the hadronic showers but contribute to **larger tails**;
- the parametrized physics list (**LHEP**) has a **reduced, longer** and **wider EM** component, a **harder spectrum of high-energy  $\pi^\pm$** , and **more 100 MeV - 1 GeV neutrons**.

# Outlook

- ❑ Compare with **Fluka**... (Alberto)
- ❑ Look at **diffraction**...
- ❑ Try some **alternatives to QGS**... (John)
- ❑ Suppress/enhance  $\eta$  ,  $\eta'$  ,  $\rho^0$  ... (Gunter)
- ❑ Revise the **inelastic cross-sections**... (Vladimir)
- ❑ Revise the **elastic scattering**... (Mikhail)
- ❑ Check **neutron production/transportation**... (Alex)
- ❑ ... *(suggestions are welcome!)*

Our understanding of the hadronic shower development is progressing... but still the LHC experiments are waiting for concrete improvements!