4.4 Comparison of the DREAM data and 4th simulations

Make a proper comparison of the DREAM data and the simulations (with/without BGO) to validate the simulation results.

4.4.1 DREAM data comparisons to 4th simulations "by hand"

For definiteness, we take 200 GeV π^- in both DREAM data (Fig. 22) and 4th ILCroot simulations (Fig. 23). The resolutions are

$$\sigma_E/E = 8.557/204.8 = 4.176\% \qquad \text{(DREAM data, Fig. 22)}$$

and

$$\sigma_E/E = 5.170/197.5 = 2.618\% \qquad \text{(ILCroot 4th simulation, Fig. 23)}$$

The simplest understanding is that this difference results from leakage in DREAM (small 1t test module) that is absent in the 4th simulation (complete 4π detector). Therefore, write

$$(\sigma_E/E)^2_{\rm DREAM} = (\sigma_E/E)^2_{\rm 4th} + (\sigma_E/E)^2_{\rm leakage}$$

or

$$(4.176\%)^2 = (2.618\%)^2 + (3.254\%)^2.$$

This leakage fluctuation of 3.254% due to side leakage is consistent with our guess of 4% leakage (based on lateral shower shapes, "Comparison of High-Energy Hadronic Shower Profiles Measured with Scintillation and Cerenkov Light", *NIM* **A584** (2008) 273, Akchurin, *et al.*, DREAM collaboration) and the reduction in this fluctuation by including the large scintillation leakage counters.

> Therefore, we can easily understand that DREAM data and 4th ILCroot simulations are compatible. There are no large, or even small, inconsistencies.

We should also remark that the essentially raw data in Fig. 22 show the best energy resolution of any proposed ILC calorimeter. There are no comparable data presented to IDAG for comparison. We would like to see a comparable distribution from the data collected in a CALICE calorimeter up to 300 GeV in the CERN H6 beam.

We follow this conclusion with a discussion of leakage measurements in the DREAM module illustrated with data. We actually understand a great deal about this dual-readout module.

The 1 kt DREAM module has leakage fluctuations of about 4%. This leakage is mostly neutrons, and our measurements of this leakage event-by-event with large scintillation counters in the July 2008 beam test show that the neutrons are anti-correlated with the electromagnetic fraction (f_{em}) event-by-event, see Fig. 24, and that about 70 neutrons are seen in the surrounding scintillation counters for a 300 GeV hadronic shower with f_{em}= 0.50. The calibration of the counters was in *mip* units using beam muons and gave an energy calibration of 0.37 GeV/*mip*. Therefore, 70 *mips* is about 26 GeV of energy in neutrons, or about 10% of the shower energy at f_{em}= 0.50. This is all in accord with expectations for hadronic showers.

Furthermore, 70 neutrons is large enough that these leakage fluctuations are Gaussian, and therefore degrade the Gaussian resolution in quadrature, that is, without introducing low-side tails in the calorimeter response. This is a point that CALICE, SiD and ILD people have misunderstood all along in their criticisms of DREAM data. In a thin calorimeter (5.5-6.7 $\lambda_{\rm int}$) leakage fluctuations out the back **will result in low-side tails**, but this is merely a direct consequence of a shallow calorimeter. This is a problem for the many CALICE calorimeters, not for the DREAM module.

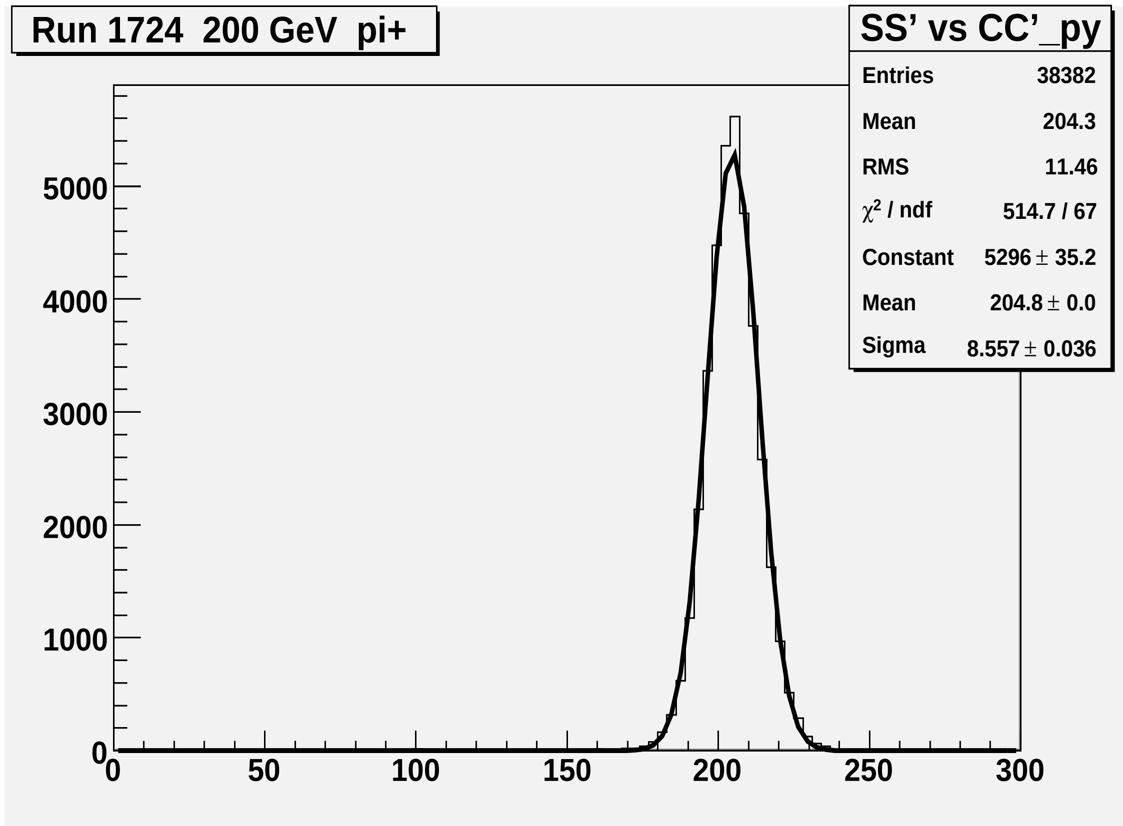


Figure 22: Dual-readout response of the BGO+DREAM module to 200 GeV π^- in CERN H4 beam. This distribution with energy resolution of $\sigma_E/E = 4.2\%$ is essentially raw data from the July 2008 DREAM test.

A direct measure of the energy degradation of DREAM due to neutron leakage is shown in Fig. 25 showing a 15% improvement in energy resolution when the scintillation leakage-counters are added to the DREAM scintillation signal.

All of these data and simulations are consistent. In the next section, we perform a direct detailed simulation of the DREAM module *plus* the BGO array in front *plus* the large area scintillation counters surrounding DREAM .

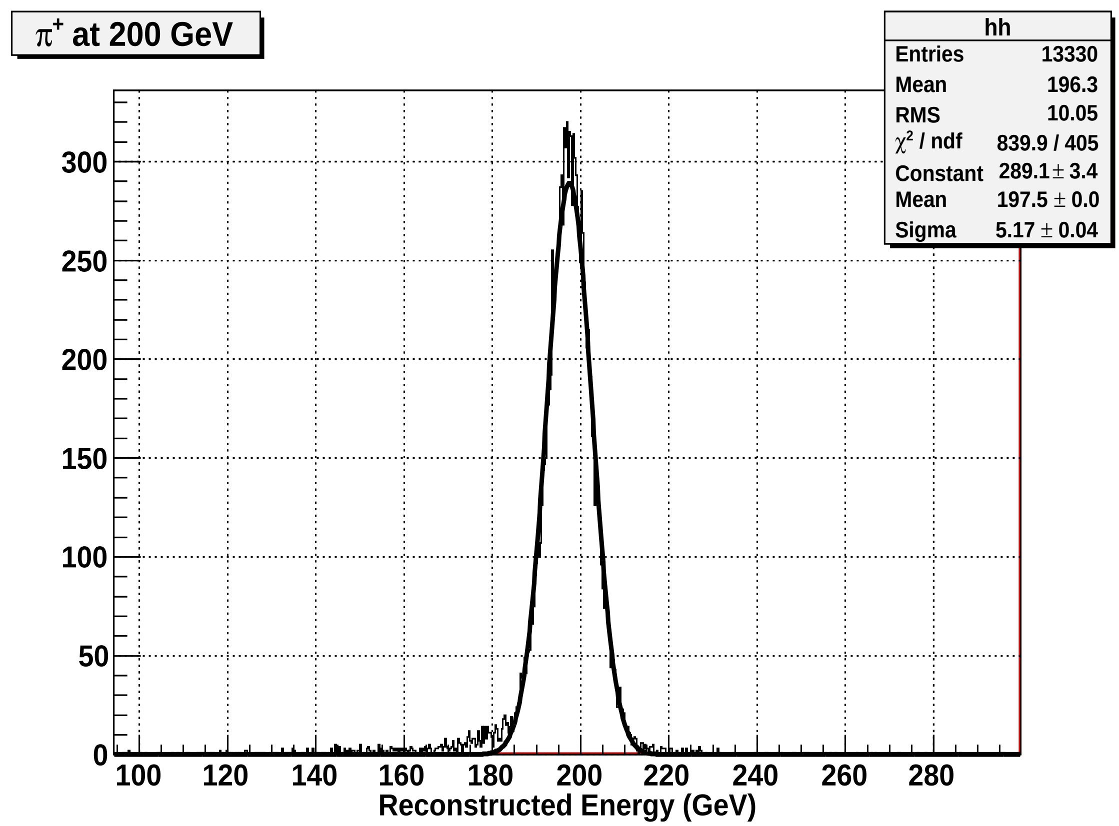


Figure 23: Dual-readout response of the 4th BGO+fiber calorimeter to 200 GeV π^- in ILCroot simulations.

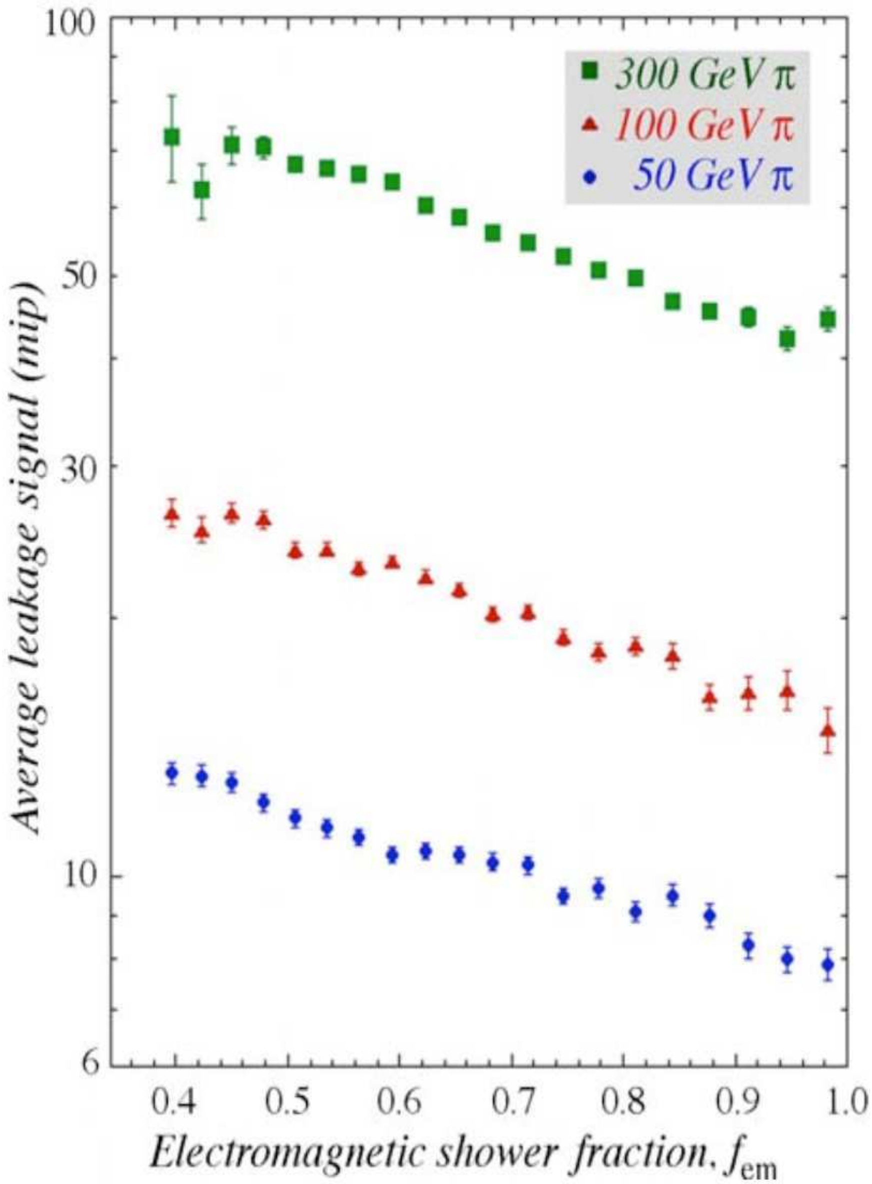


Figure 24: Leakage signal of mostly neutrons *vs.* the EM fraction in hadronic showers at 50, 100, and 300 GeV (DREAM data, submitted to NIM).

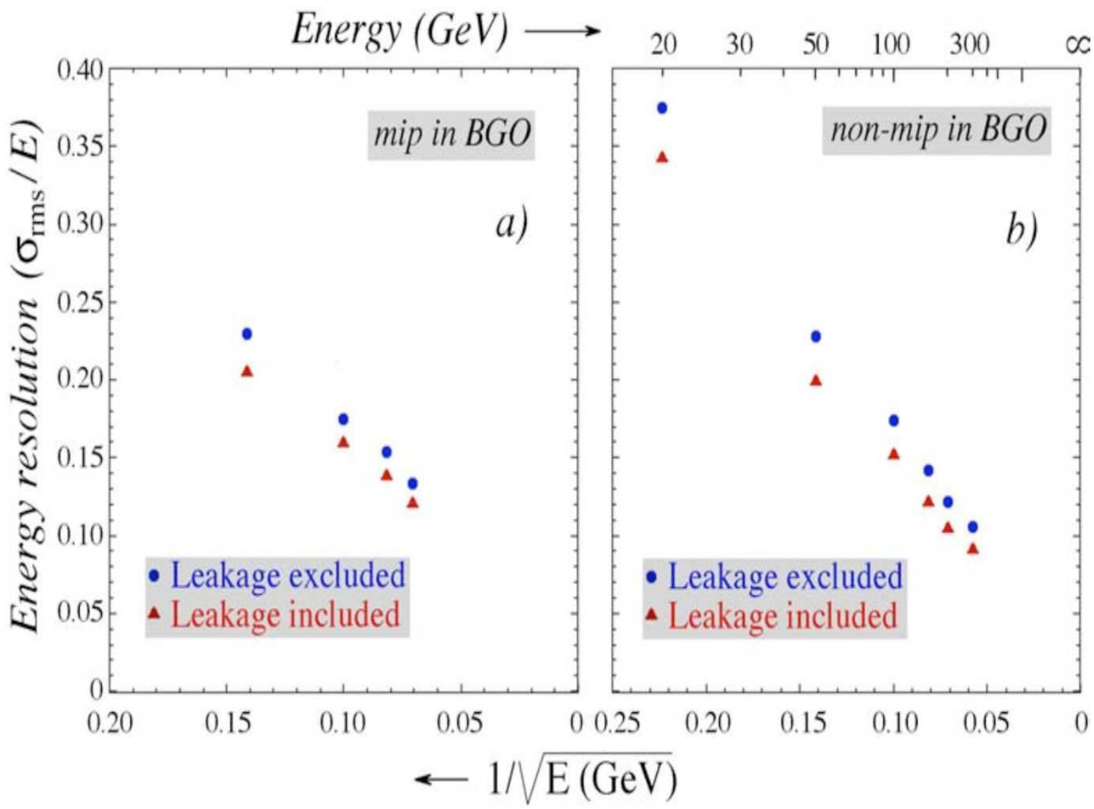


Figure 25: The energy resolution improvement attained by adding the leakage signal to the scintillations (S) signal of DREAM (submitted to NIM).

4.4.2 Direct simulation of the DREAM module: ILCroot 4th simulation

(Vito Di Benedetto, vito.dibenedetto@le.infn.it)

A direct and detailed simulation has been made of the DREAM module as tested in June 2004 and published "Hadron and Jet Detection with a Dual-Readout Calorimeter," N. Akchurin *et al.*, *Nucl. Instr. and Meths.* **A537** (2005) 537561.

Following figures are direct comparisons of DREAM data (top frames) and ILCroot simulation of the DREAM module (bottom frames). The quantities measured in DREAM and simulated with ILCroot are listed here:

Fig. 26 The mean scintillation signal as a function of $\pi^{\pm}$ beam energy.

Fig. 27 Scintillation signal *vs.* Cerenkov signal for 100 GeV pions.

Fig. 28 DREAM : Distributions of scintillation (S) and Cerenkov (C) signals for 100 GeV pions.

Fig. 29 ILCroot simulation: Distributions of scintillation (S) [top] and Cerenkov [bottom].

Fig. 30 Leakage-suppressed resolution function for DREAM data, (b) in upper frame, and ILCroot simulated resolution *using the same constants as used in data* to calculate the dual-readout energy.

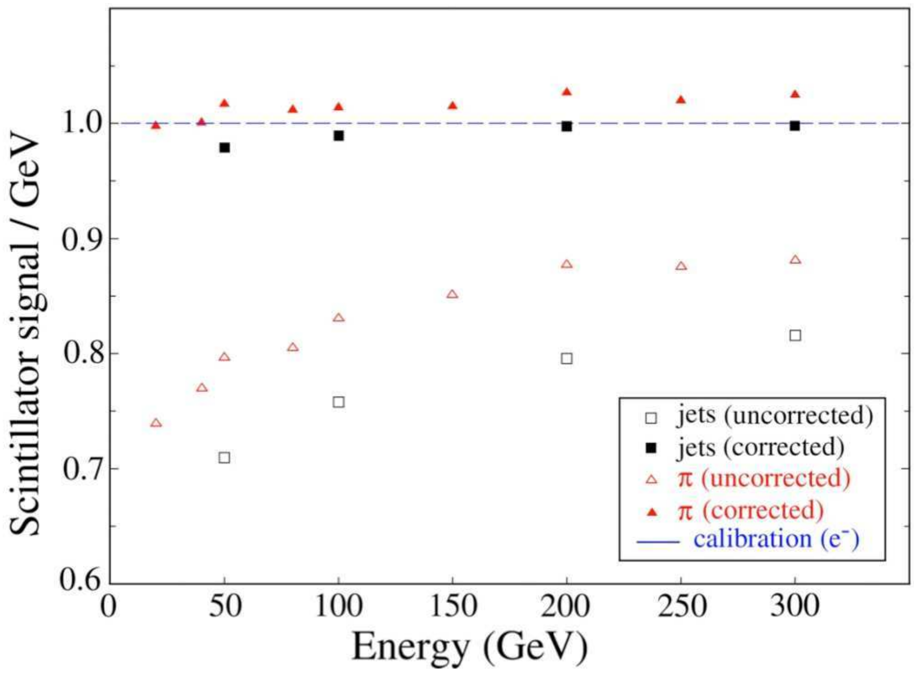
Fig. 31 The dual-readout scintillation signal corrected for EM fraction (effectively a rotation in the S-C plane), for DREAM data (top frame) and ILCroot simulation (bottom frame).

Fig. 32 The non-dual-readout individual resolutions in the scintillation and Cerenkov signals from DREAM data (top) and from ILCroot simulations (bottom).

Fig. 33 Leakage-suppressed energy resolution for pions, in DREAM data (top) and in ILCroot simulations (bottom).

Fig. 34 The electron resolutions in the scintillation and Cerenkov signals from DREAM data (top) and from ILCroot simulations (bottom).

These extensive and detailed comparisons between data and simulations are extremely good. This is a direct simulation with the 4th ILCroot framework executing the FLUKA hadronic shower code. There is no such thing as "tuning a monte carlo" here. Just a direct instrument simulation.



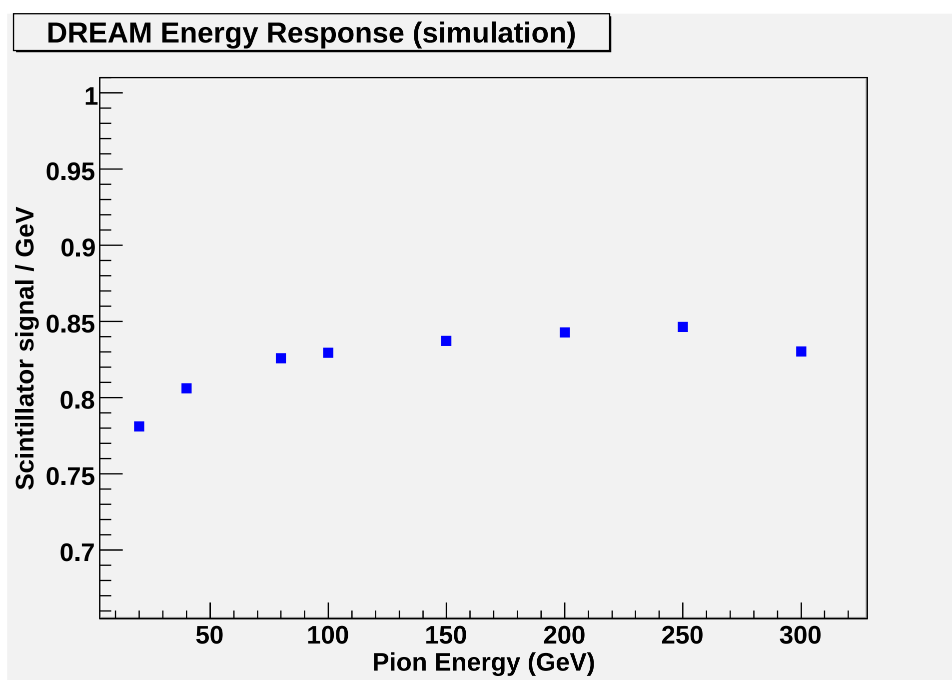


Figure 26: Average scintillation signal *vs.* pion beam energy: DREAM data (top), and 4th ILCroot simulation of DREAM (bottom). The ILCroot simulation should be compared to the red open triangles.

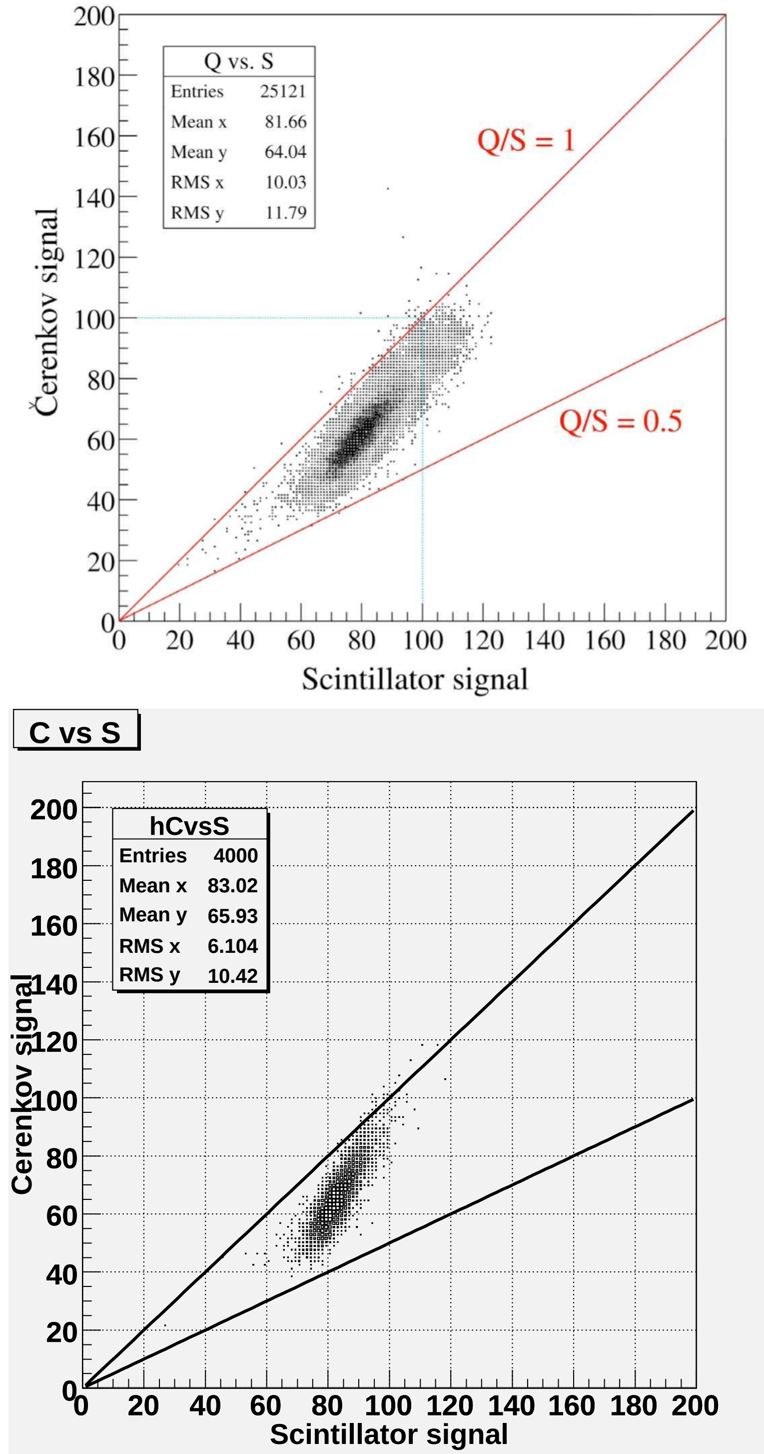


Figure 27: Scintillation signal *vs.* Cerenkov signal for 100 GeV pions: DREAM data (top), and 4th ILCroot simulation of DREAM (bottom).

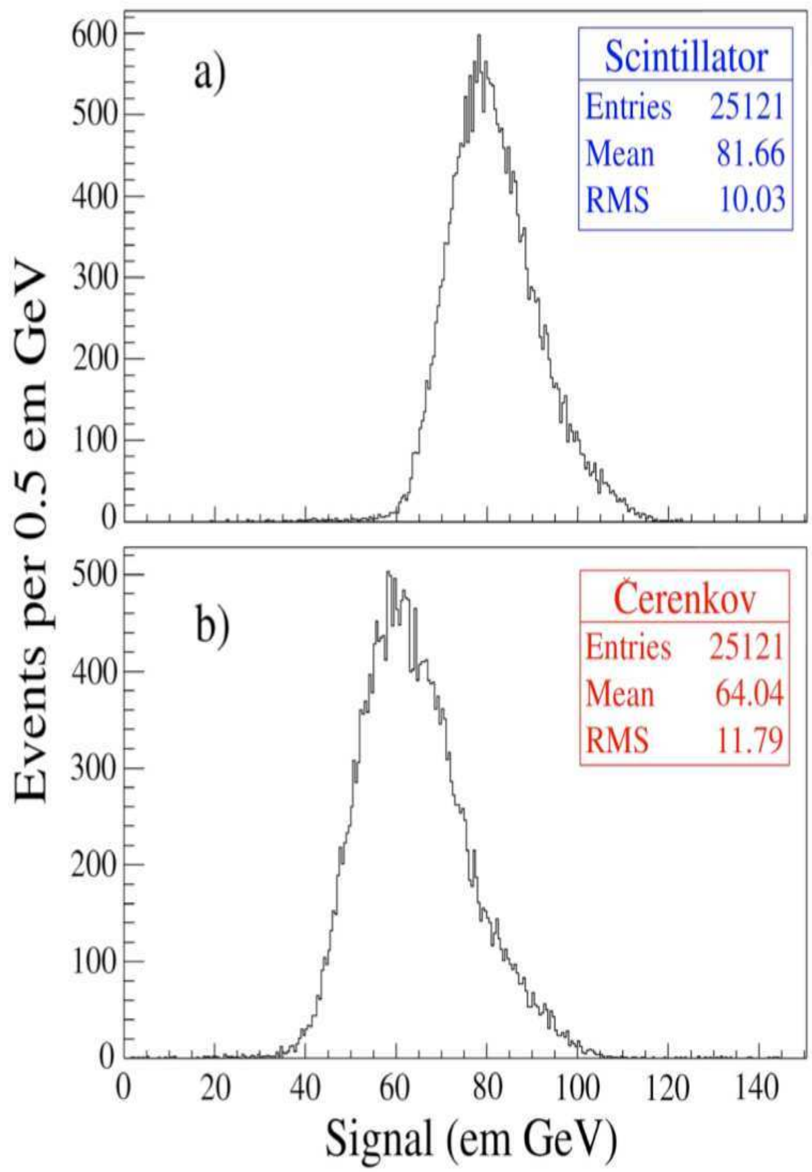


Figure 28: DREAM data: scintillation and Cerenkov signal distributions for 100 GeV pions.

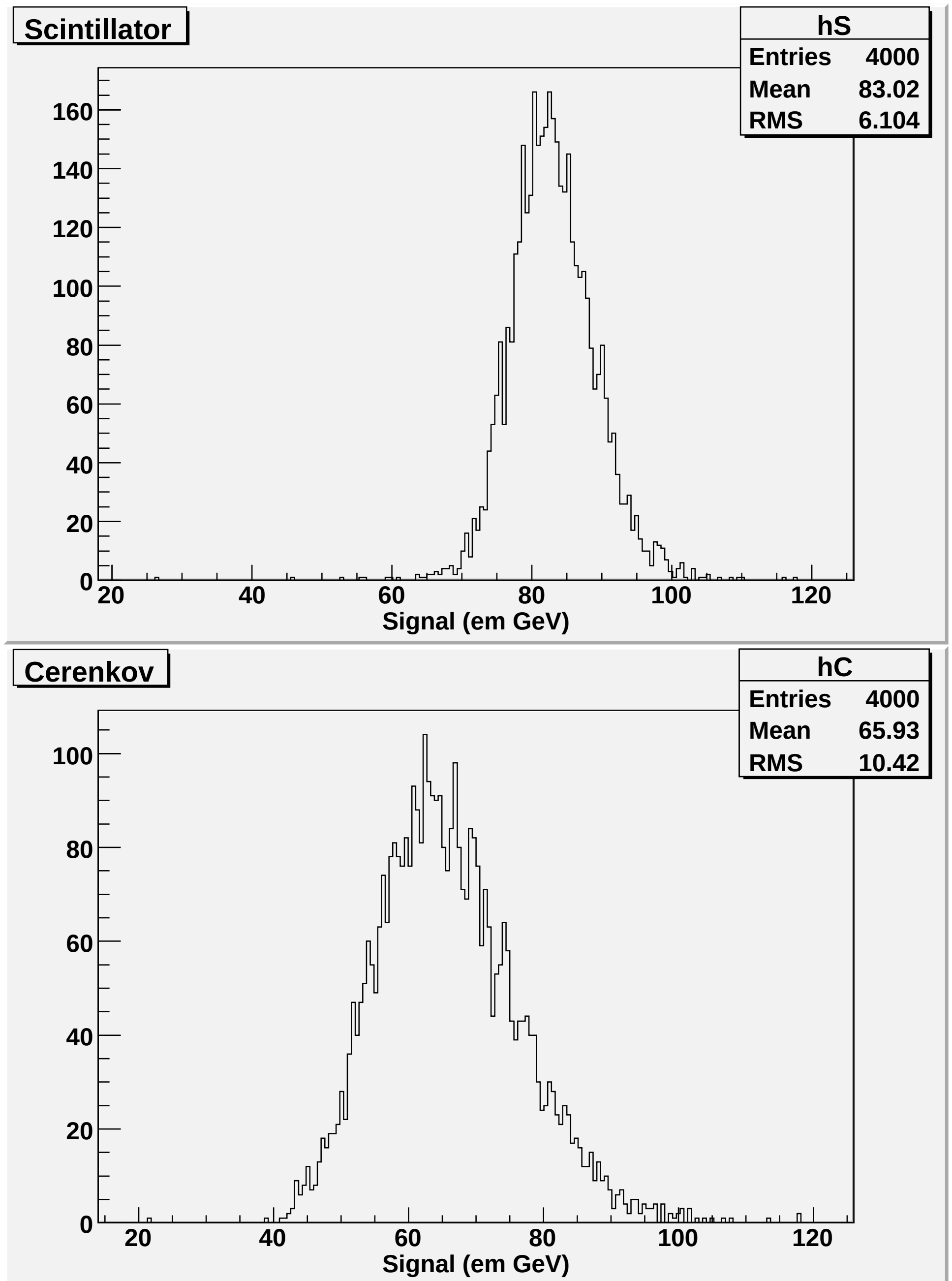


Figure 29: ILCroot simulation: scintillation signal and Cerenkov signal for 100 GeV pions.

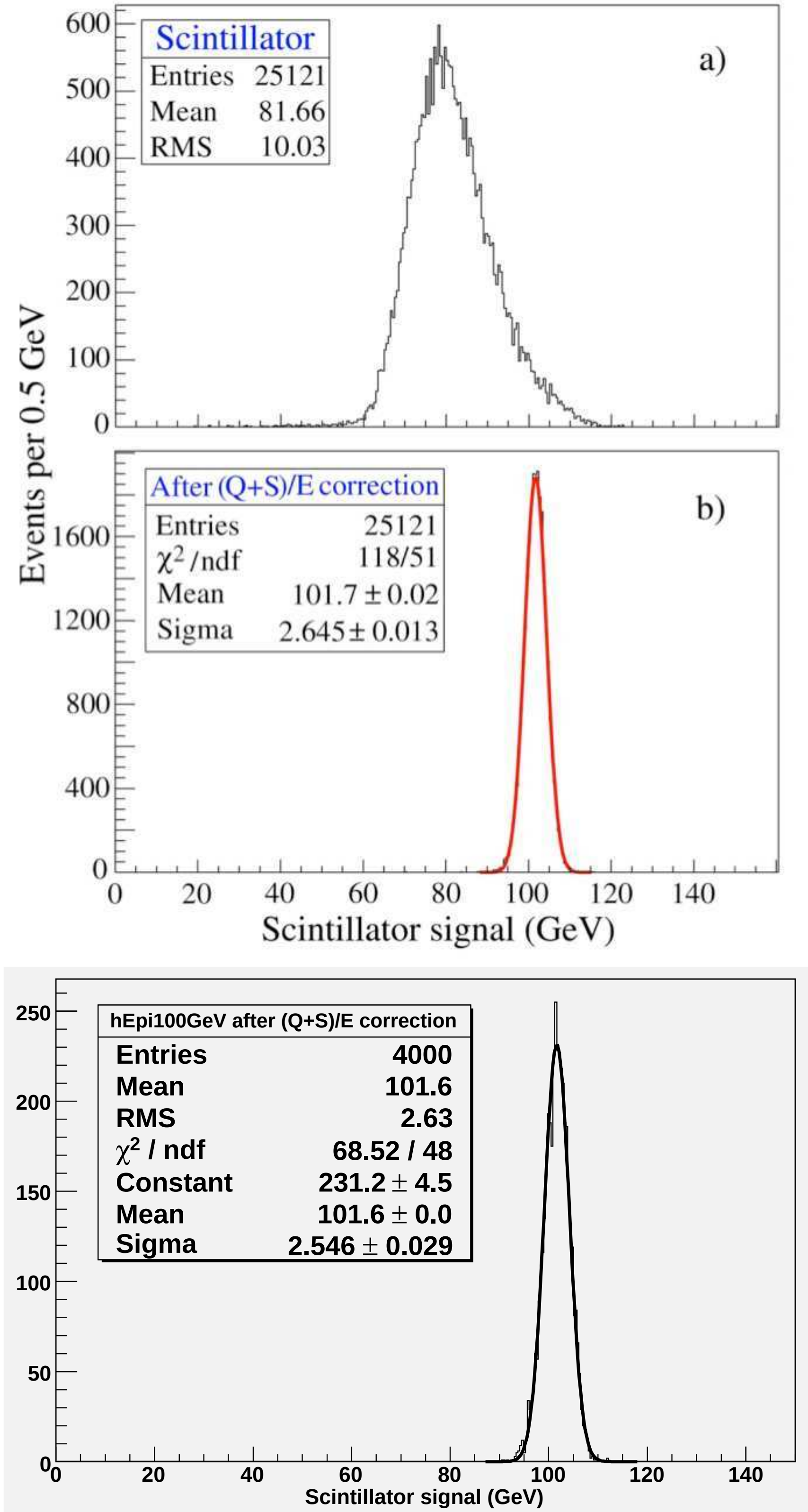


Figure 30: Leakage-suppressed resolution function for DREAM data, (b) in upper frame, and ILCroot simulated resolution *using the same constants as used in data* to calculate the dual-readout energy.

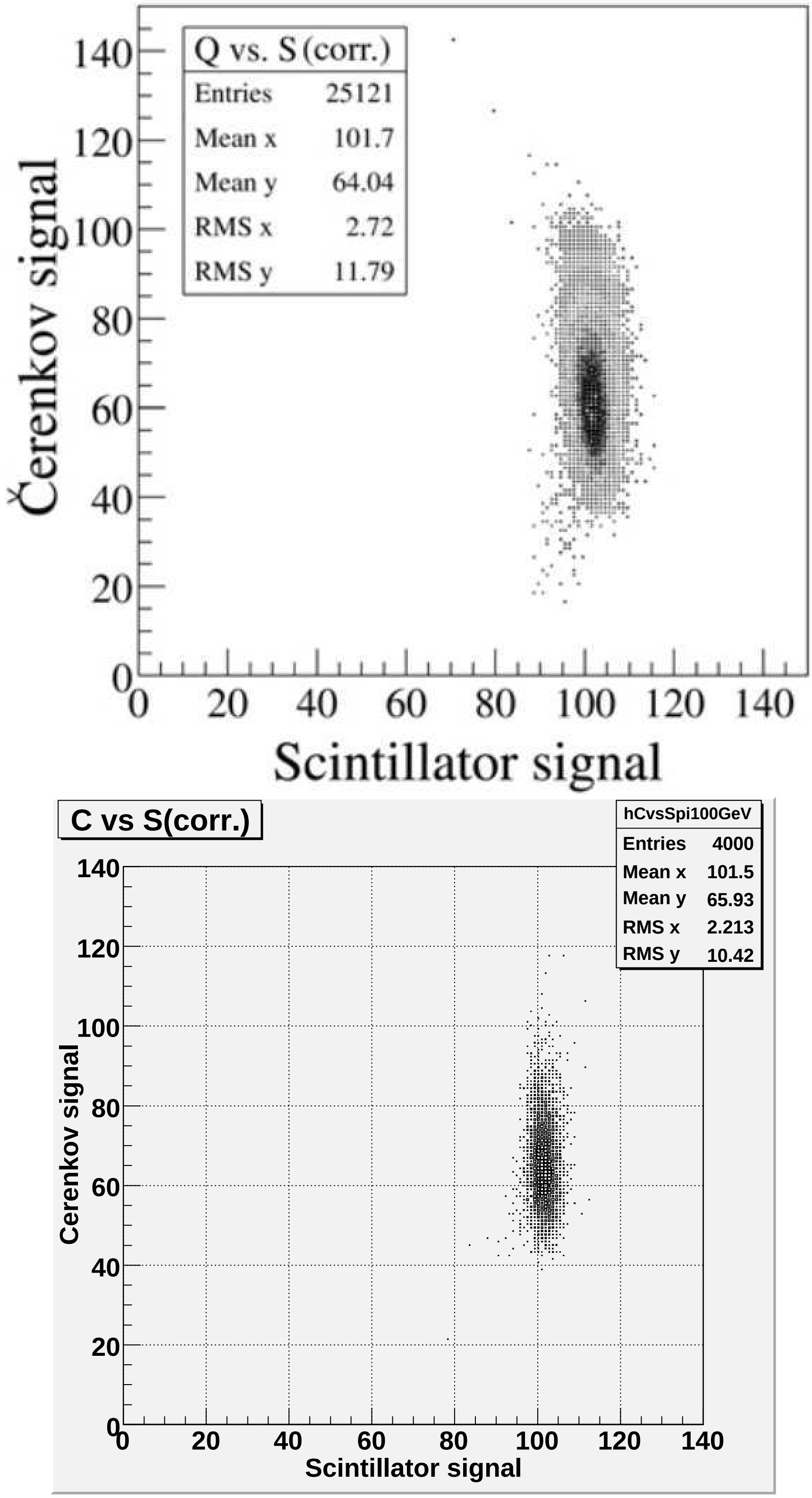


Figure 31: The dual-readout scintillation signal corrected for EM fraction (effectively a rotation in the S-C plane), for DREAM data (top frame) and ILCroot simulation (bottom frame).

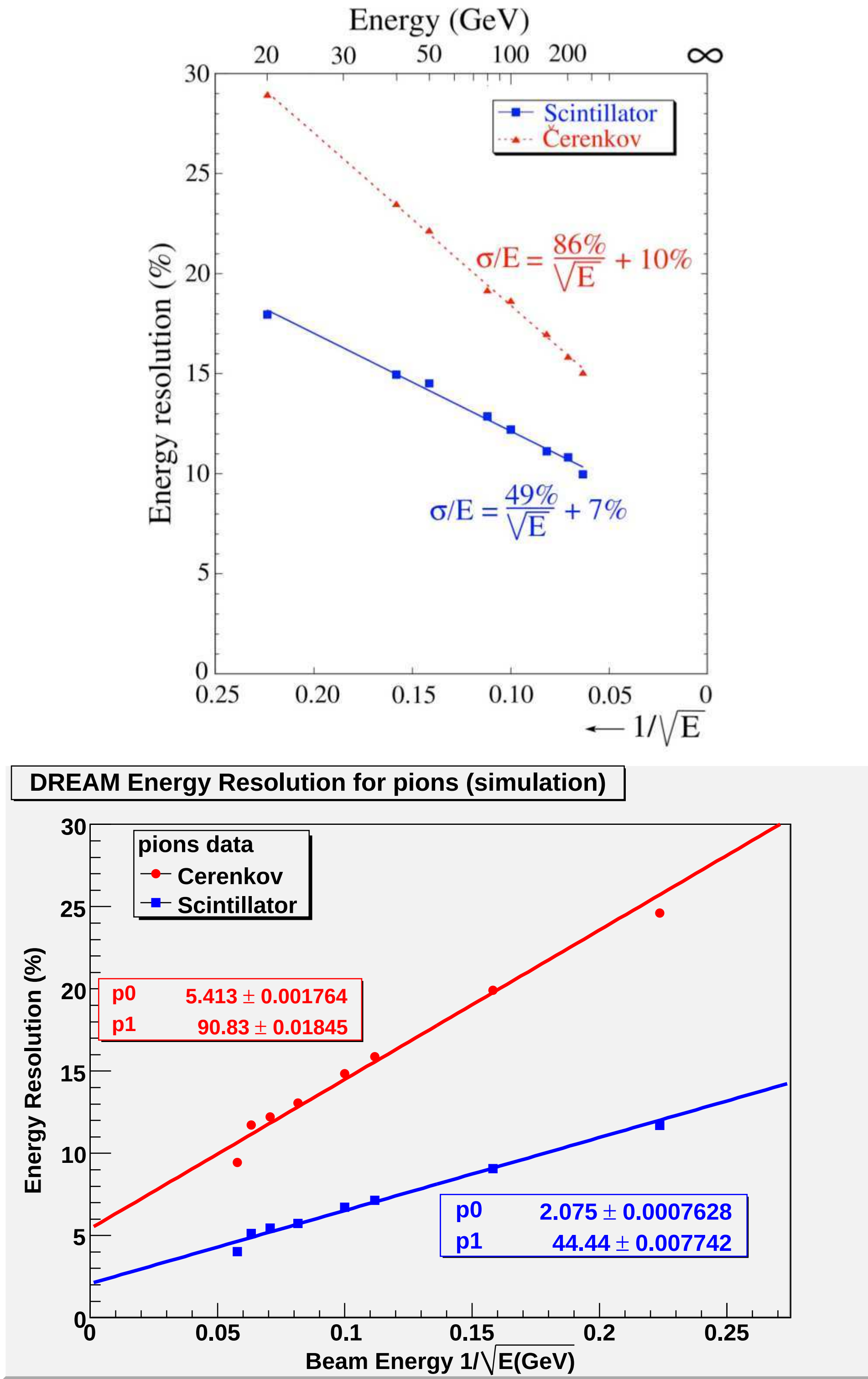


Figure 32: The non-dual-readout individual resolutions in the scintillation and Cerenkov signals from DREAM data (top) and from ILCroot simulations (bottom)

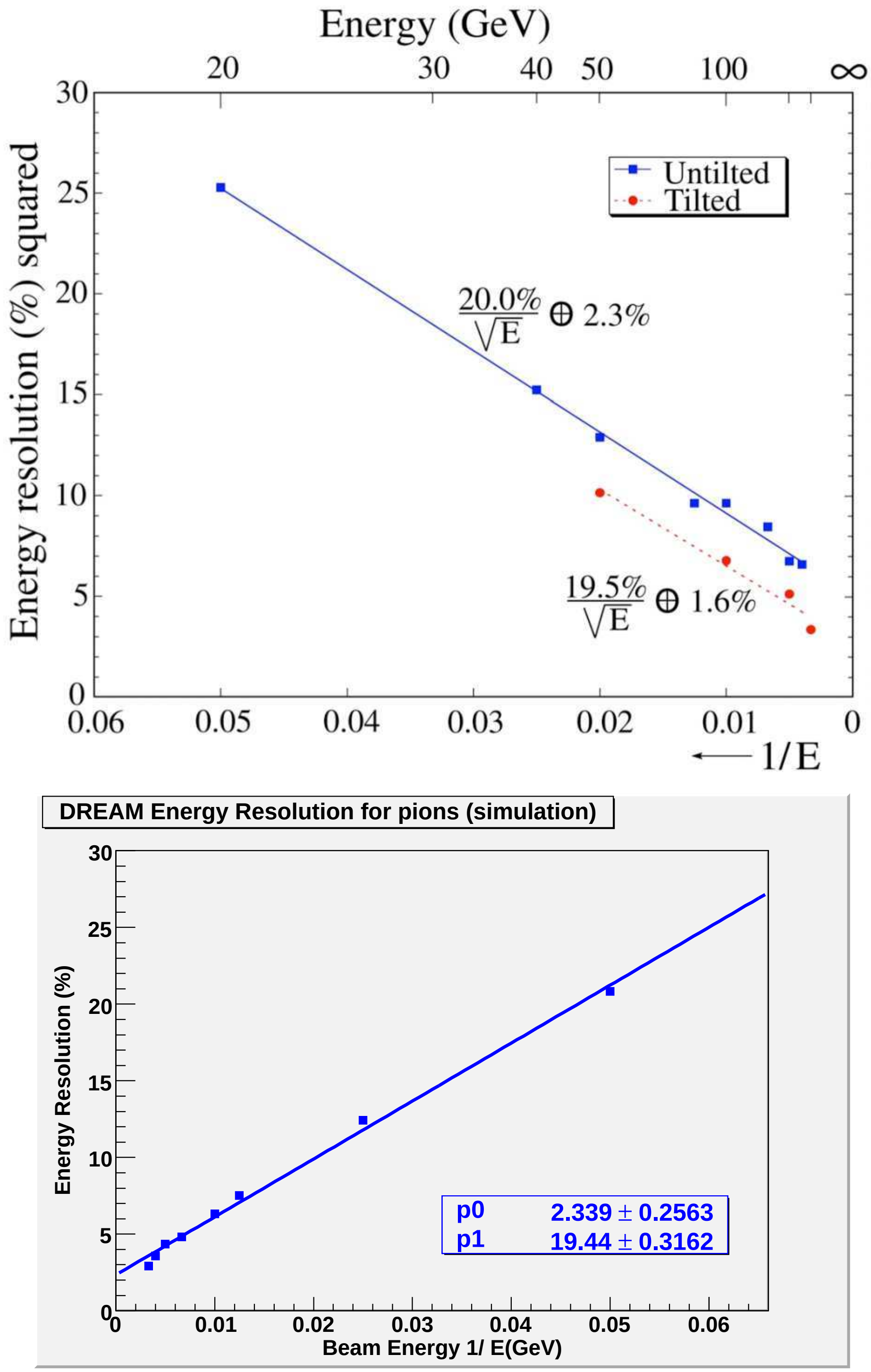


Figure 33: Leakage-suppressed energy resolution for pions, in DREAM data (top) and in ILCroot simulations (bottom).

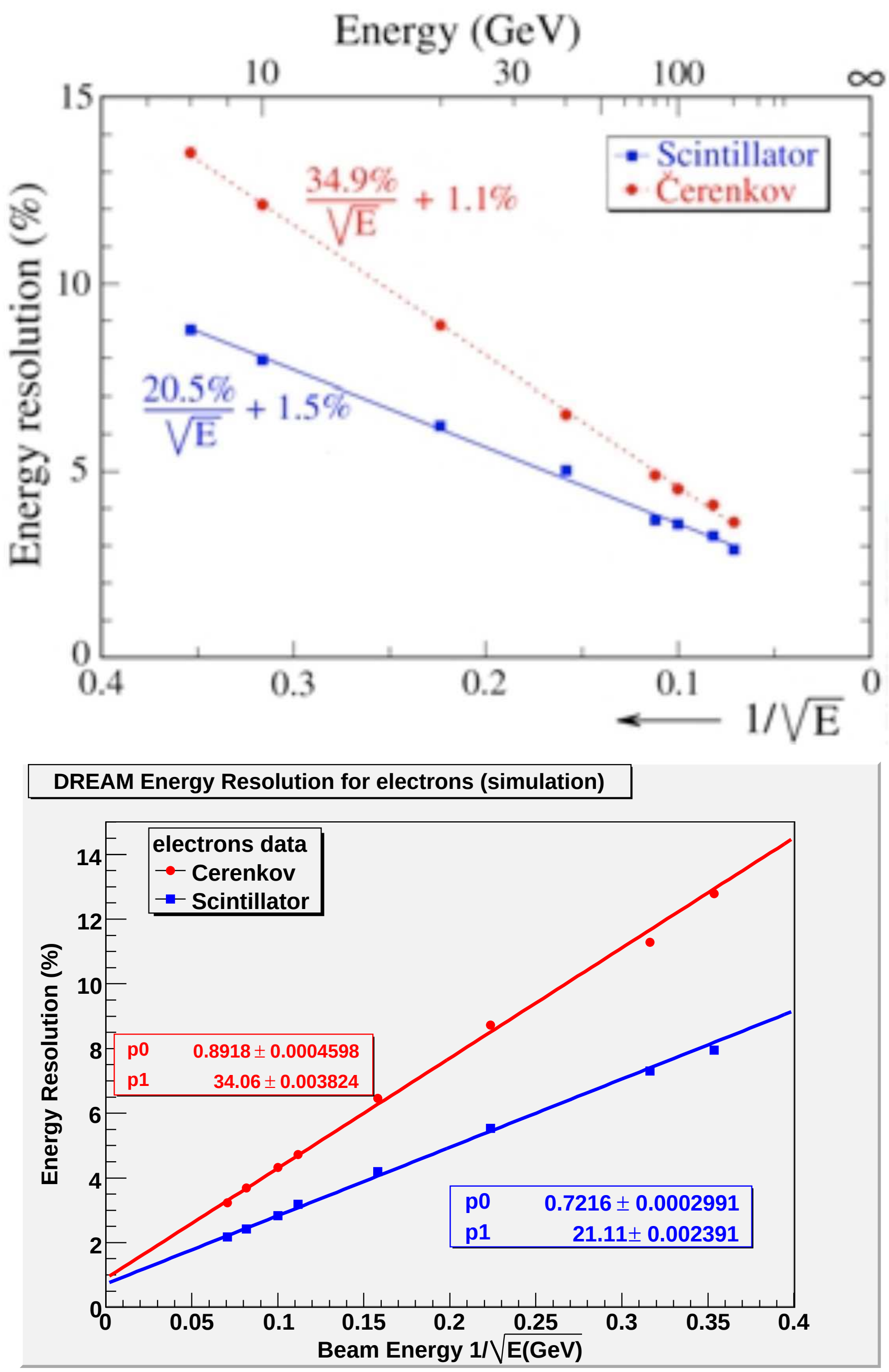


Figure 34: The electron resolutions in the scintillation and Cerenkov signals from DREAM data (top) and from ILCroot simulations (bottom)