Simulation Studies of a Homogeneous Total Absorption Dual Readout Calorimeter

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- Summary

Calorimetry

"Calorimetry refers to the detection of particles, and measurement of their properties, through total absorption in a block of matter, called a calorimeter."

[R. Wigmans, 2000]

A simple concept, what is the big deal about its implementation?

The most energetic particles in modern accelerator experiments are measured in units of TeV

$$1 \ TeV = 10^{12} \ eV$$

whereas

$$1 \ calorie \sim 10^7 \ TeV$$

Rise in temperature ~ negligible! ⟶ Sophisticated methods are needed to determine the particle properties

Calorimeter Types

Some calorimeters are built in two sections:

• **Electromagnetic**: Finer segmentation, smaller volume, enough to contain an e&m shower, electronics are usually more precise.

• **Hadronic**: Coarser segmentation, larger volume to contain a hadronic shower, usually worse resolution than the e&m section.

Calorimeters can also be:

Tracking detector

Solenoidal magnet

EM calorimeter

Hadron calorimeter

Muon detector

Fig. 1.1. Endview cross-section of the ATLAS detector

$$\frac{\sigma_E}{E} \sim \frac{1}{\sqrt{E}} \quad vs. \quad \frac{\sigma_p}{p} \sim p$$

• **Sampling**: Particle absorption and signal generation are exercised by different materials:

    active medium: generates the light that forms the basis for the signals (*crystal, plastic,...*), passive medium: usually a high density material that absorbs the particle (*copper, lead, iron, ...*)

• **Homogeneous**: Entire volume is sensitive to the particles and may contribute to the signals generated by the detector.
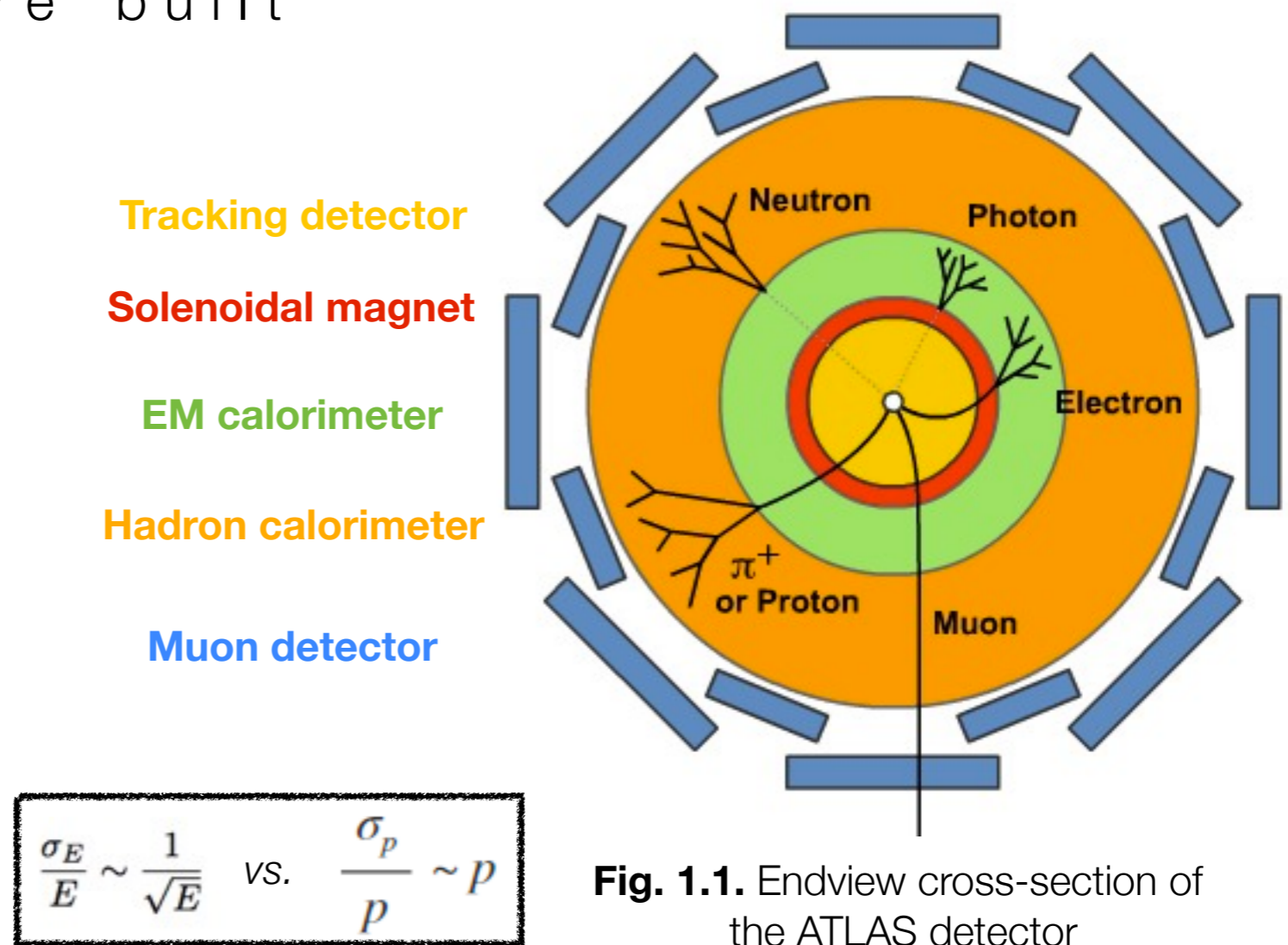
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Principle of Operation

- **Incoming particle initiates particle shower:** When a particle traverses matter, it will generally interact and *lose a fraction of its energy* in doing so.

- **Energy is deposited in the calorimeter,** in form of *heat*, *ionization*, *excitation of atoms*, *Cerenkov light* (*different calorimeter types use different detection mechanisms to measure the deposited energy*)

> For e&m showers,
> *measured energy ~ energy of incoming particle*
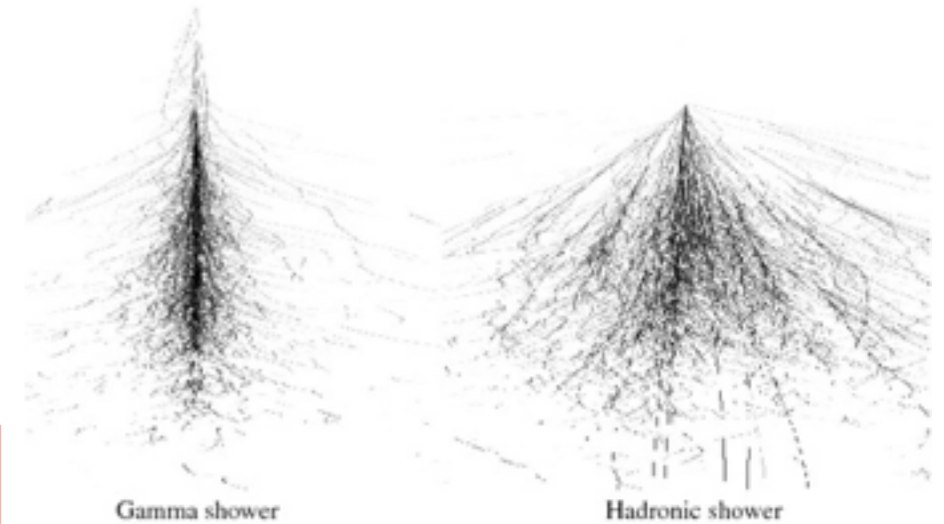

Gamma shower   Hadronic shower

Fig. 1.2. Shower development

Detection Mechanisms

- **Scintillation light:** produced when excited atoms return to ground state.

- **Čerenkov light:** produced when a charged particle travels faster than the speed of light in a certain medium.

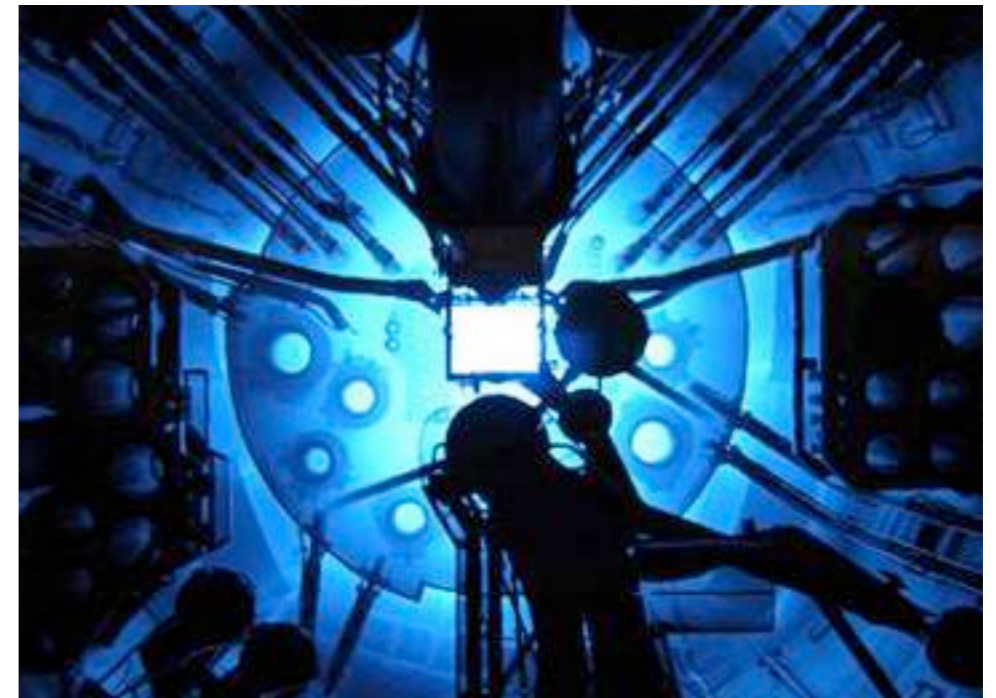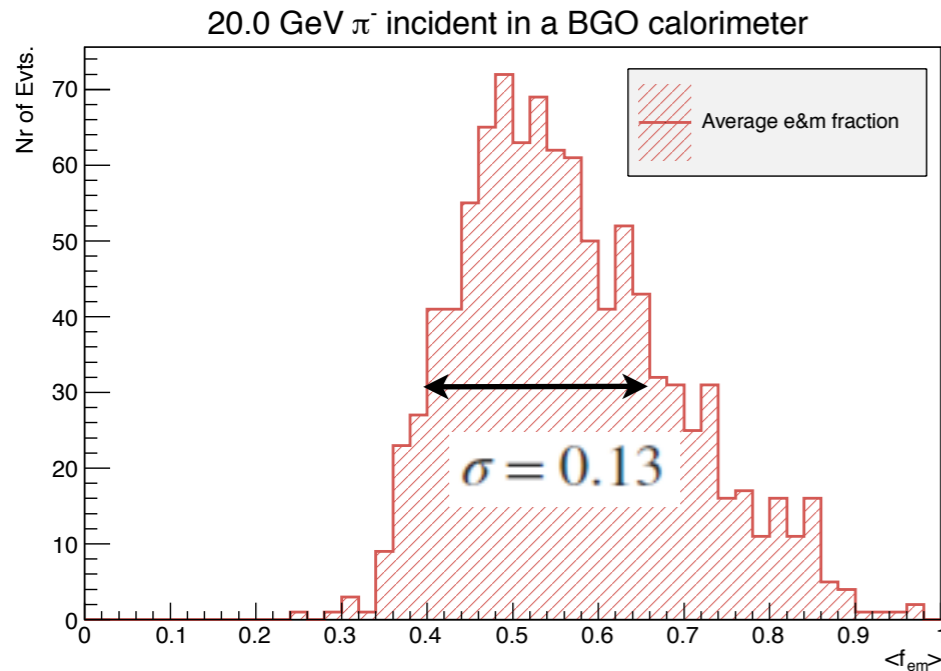$$\beta = \frac{v}{c} > \frac{1}{n}$$

Fig. 1.3. Cerenkov light in water-cooled reactor [5]

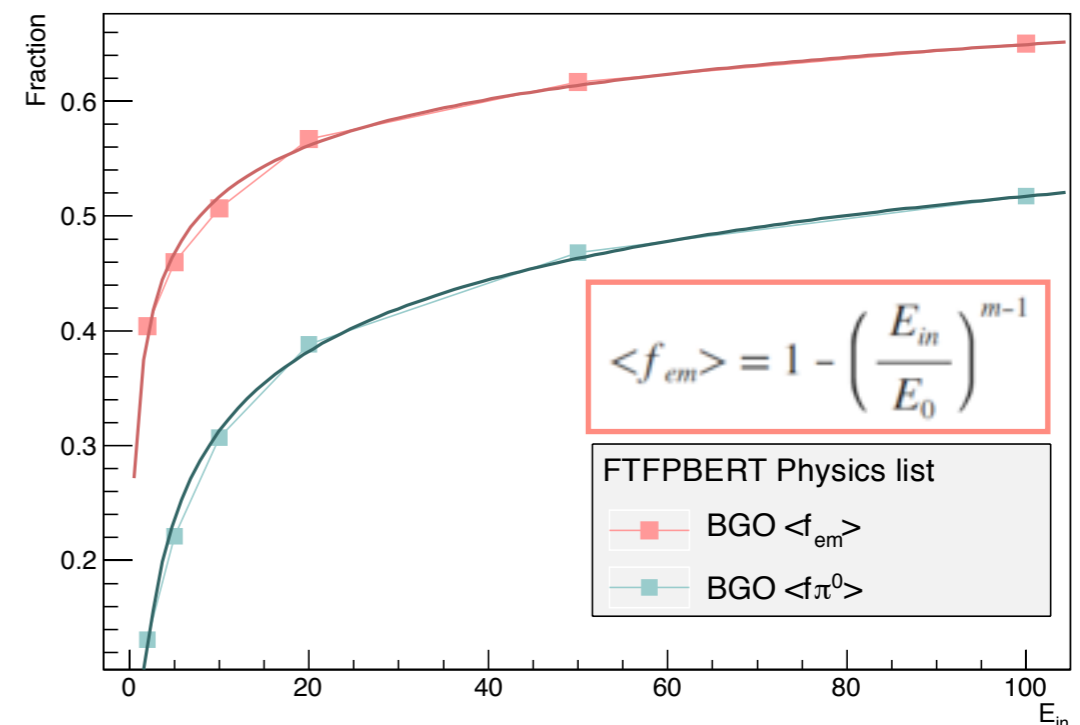# Average value of Electromagnetic Fraction $\langle f_{em} \rangle$

20.0 GeV π^- incident in a BGO calorimeter

$\sigma = 0.13$

• Some people defines it as the energy deposited in the calorimeter by means of the kinetic energy of $\pi^{0's}$

• For this study, we define it as the energy deposited by any electromagnetic-interacting particle: e^+, e^-, γ

The electromagnetic fraction varies strongly from event to event. Possible explanations include:

• Processes occurring in the early phase of shower development.

• The average fraction of the initial hadron energy converted into neutral pions increases with energy.

• Baryon number conservation induces a smaller electromagnetic fraction proton-induced showers than in pion-induced showers.

Physics list FTFPBERT
BGO $\sigma_{f_{em}}$
BGO $\sigma_{f_{\pi^0}}$

$$\langle f_{em} \rangle = 1 - \left(\frac{E_{in}}{E_0} \right)^{m-1}$$

FTFPBERT Physics list
BGO $\langle f_{em} \rangle$
BGO $\langle f\pi^0 \rangle$

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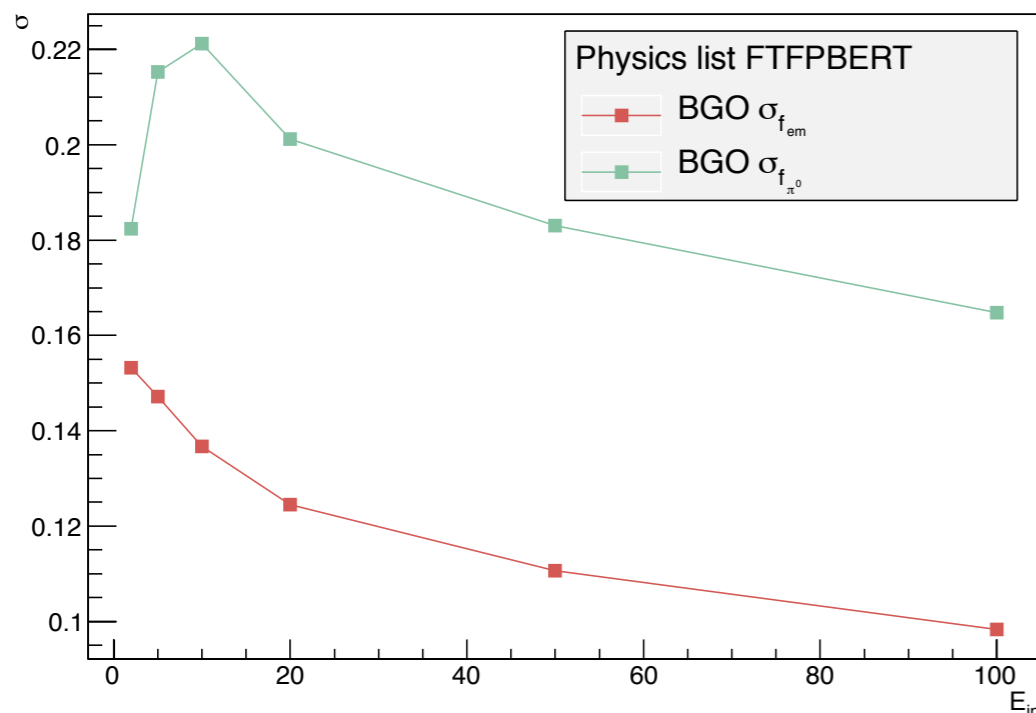
Dual Readout Calorimetry

Measurement of both the ionization/scintillation and the Cherenkov signals generated by a hadronic shower in order to determine on an event by event basis the electromagnetic fraction of the shower and so to cancel/correct for this source of fluctuation that degrades the energy resolution of the calorimeter.
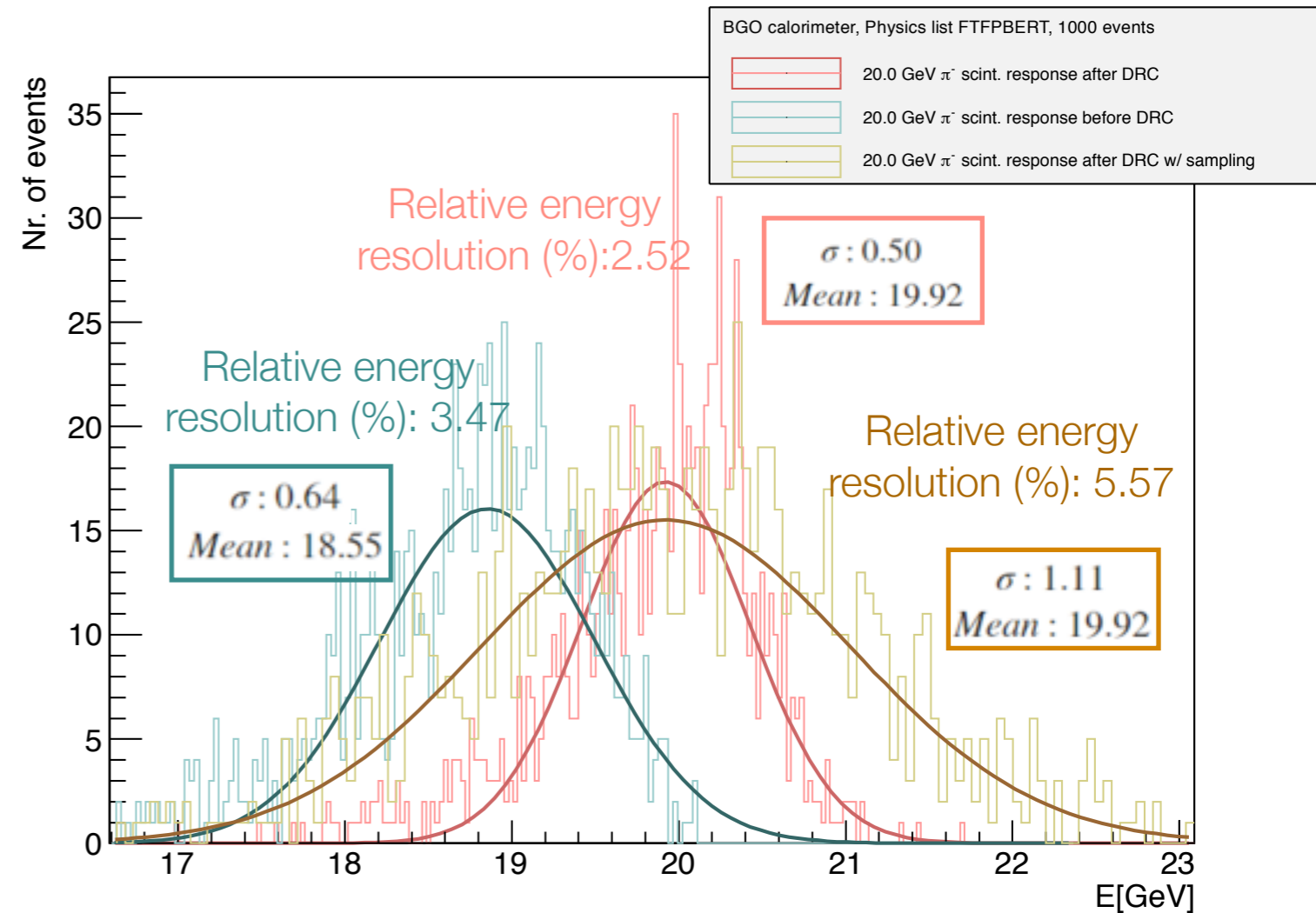
The energy response for scintillation and Cerenkov signals can be described as (respectively):

$$\frac{S}{E} = f_{em} \cdot e + (1 - f_{em})h_s$$

$$\frac{C}{E} = f_{em} \cdot e + (1 - f_{em})h_C$$

where e is usually set to unity since we calibrate for this response to be equal to one. By doing this and then taking the ration of both response equations we can eliminate the contribution from the electromagnetic fraction:

$$E = S\left[\frac{(1 - h_C) - C/S(1 - h_S)}{h_s - h_c}\right] \quad for\ h_c \ll h_s$$

BGO calorimeter, Physics list FTFPBERT, 1000 events

20.0 GeV π^- scint. response after DRC

20.0 GeV π^- scint. response before DRC

20.0 GeV π^- scint. response after DRC w/ sampling

Nr. of events

Relative energy resolution (%):2.52

$\sigma : 0.50$
$Mean : 19.92$

Relative energy resolution (%): 3.47

$\sigma : 0.64$
$Mean : 18.55$

Relative energy resolution (%): 5.57

$\sigma : 1.11$
$Mean : 19.92$

E[GeV]

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Motivation for a Homogeneous Total Absorption Dual Readout Calorimeter

The next generation of lepton collider detectors will emphasize on precision for all sub-detectors systems:

- A benchmark of this new type of calorimeter would be to be able to distinguish W and Z vector bosons in their hadronic decay mode.

  This requires a di-jet mass resolution better than the natural width of these bosons and hence a jet energy resolution better than 3%... for hadron calorimetry this implies an energy resolution of a factor of 2 better than previously achieved by any large-scale experiment!

- The use of Cerenkov light might provide a fast signal when timing is critical.

Higgs factory?

Enabling Technologies

- The availability of high density($\sim 8 \ g/cm^3, \ Nuclear \ interaction \ length \sim 20.0 \ cm$) scintillating crystals/glasses (currently a R&D program to find affordable crystals).

- The availability of robust, compact, and inexpensive silicon PMT's (they work in strong magnetic fields).

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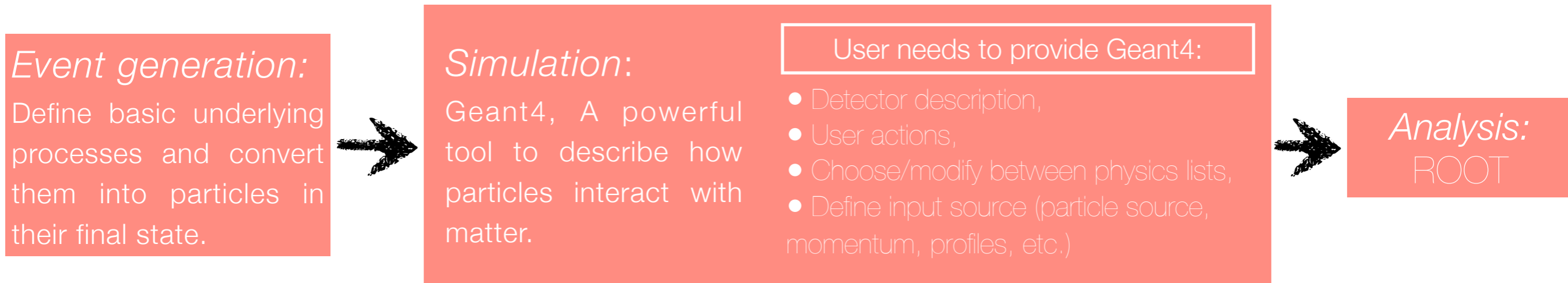# Motivation for a Homogeneous Total Absorption Dual Readout Calorimeter

The principal contributions to hadron energy resolution and non-linearity include:

Contribution	Proposed solution
Fluctuations in nuclear binding: hadronic non-linear response, different response to charged and neutral pions.	Dual Readout
Sampling fluctuations: fluctuations in the sharing of shower energy between active and passive materials in sampling calorimeters	Totally active, homogeneous
Difference in sampling fractions: fluctuations introduced from the difference in sampling fractions between different materials	Totally active, homogeneous
Leakage: Energy lost to neutrinos, muons and the tails of the shower that escape the detector volume	Total absorption

We can address these fluctuations by building a homogeneous (totally active) total absorption dual readout calorimeter!

Simulation Framework : CaTS (Calorimeter and Tracker Simulation

We could visualize the simulation process in these basic steps:

Event generation:
Define basic underlying processes and convert them into particles in their final state.

Simulation:
Geant4, A powerful tool to describe how particles interact with matter.

User needs to provide Geant4:
- Detector description,
- User actions,
- Choose/modify between physics lists,
- Define input source (particle source, momentum, profiles, etc.)

Analysis:
ROOT

CaTS -> A step in between Event generation and Geant4 simulation tools

- Facilitates the description of the detector geometry by using a gdml file containing relevant optical properties [refraction index, absorption length, etc..]
- Provides
  - ▸ the possibility of writing the simulated events [persistency],
  - ▸ input information [particle gun, general purpose particle source, Hep-evt],
  - ▸ sensitive detectors and Hit classes which are attached to the detector volume, and
  - ▸ an analysis framework and the capability of filling histograms in various user actions.
- Allows for
  - ▸ total volume (general) studies as well as for detailed study of single calorimeter cells, and
  - ▸ the modification of the detector settings without having to recompile.

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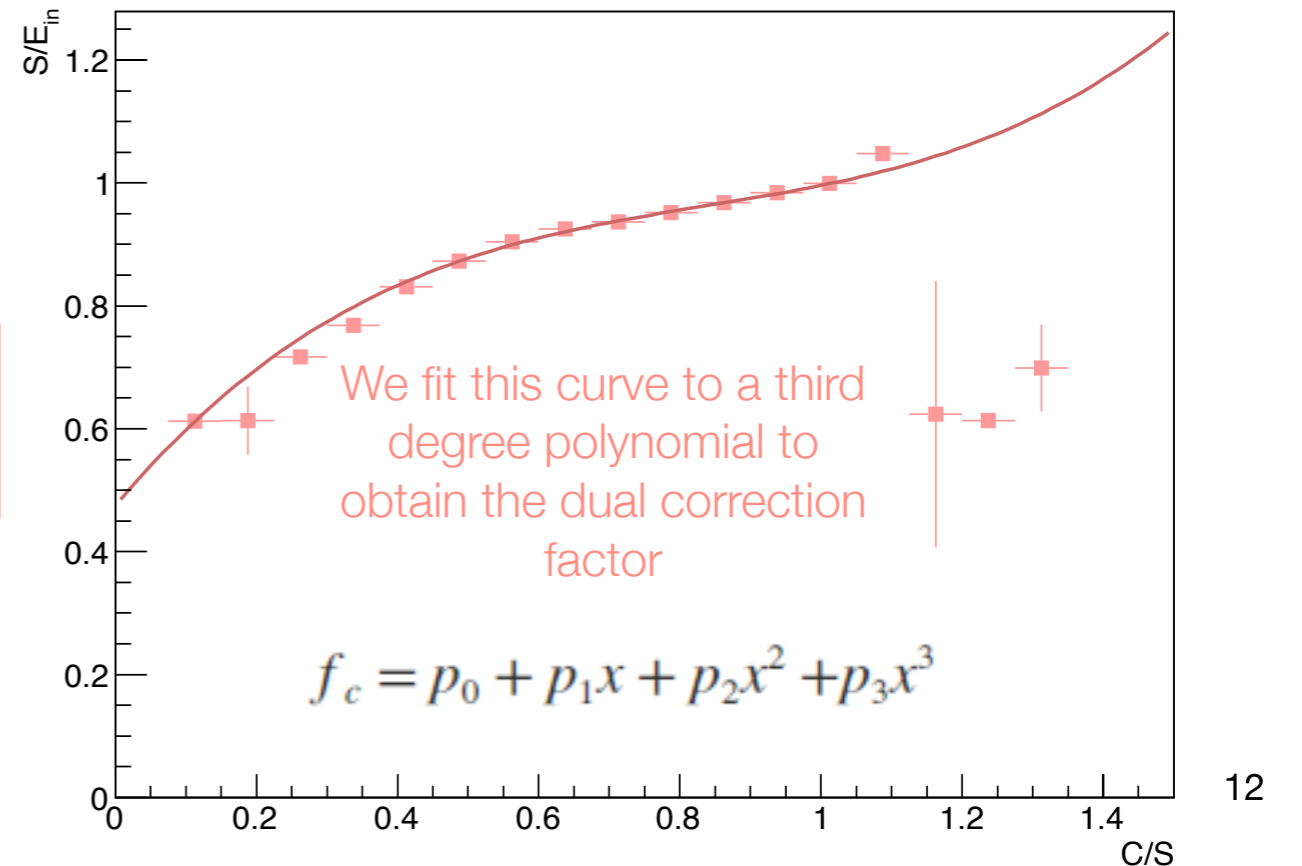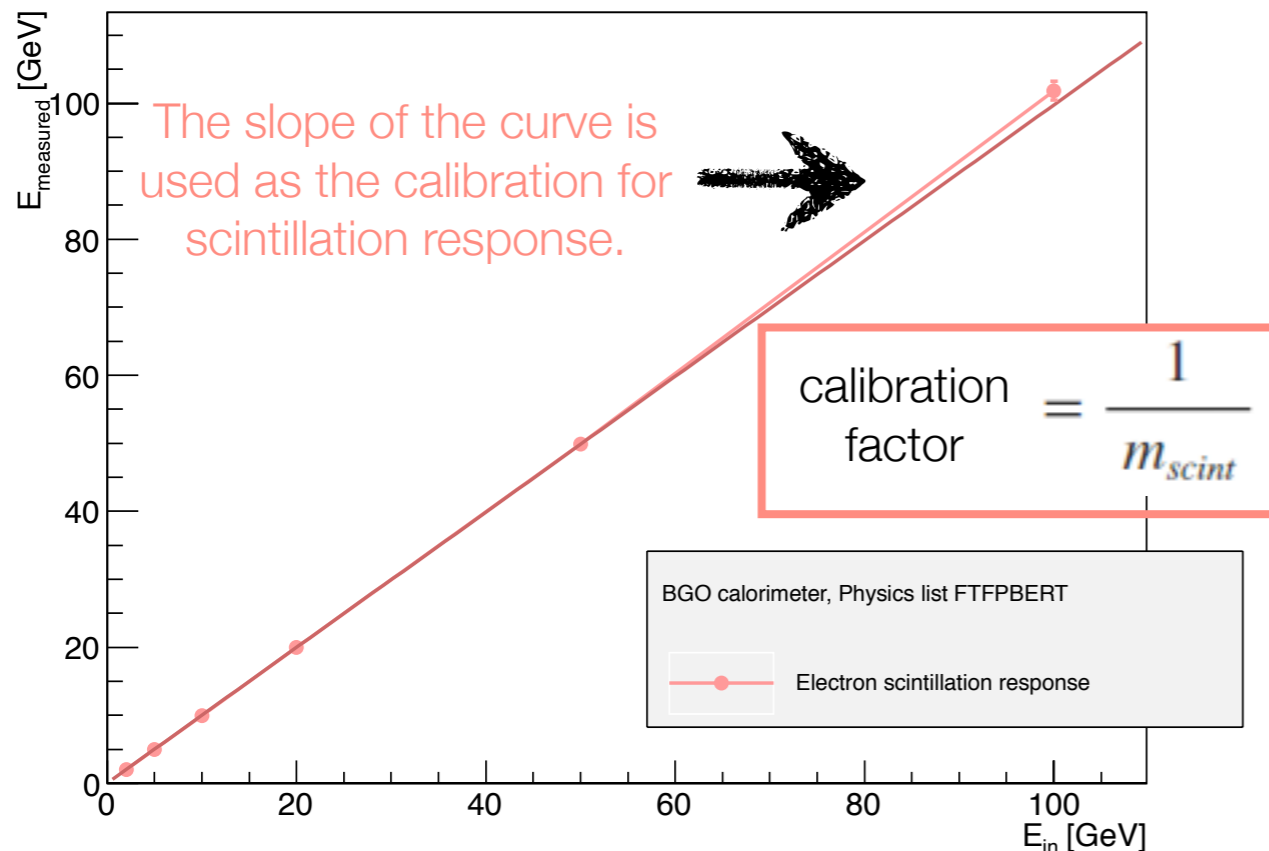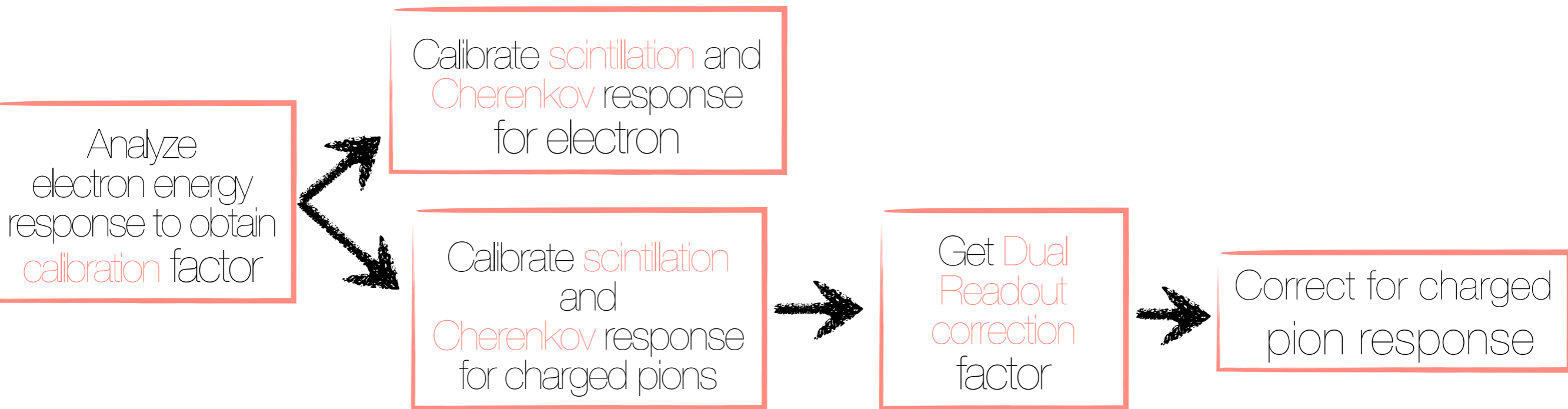# Simulation Framework : CaTS (Calorimeter and Tracker Simulation

Created by Hans Wenzel, Paul Russo, Peter Hansen

Single event for 2.0 GeV pion

100 cubes

2.5 cm
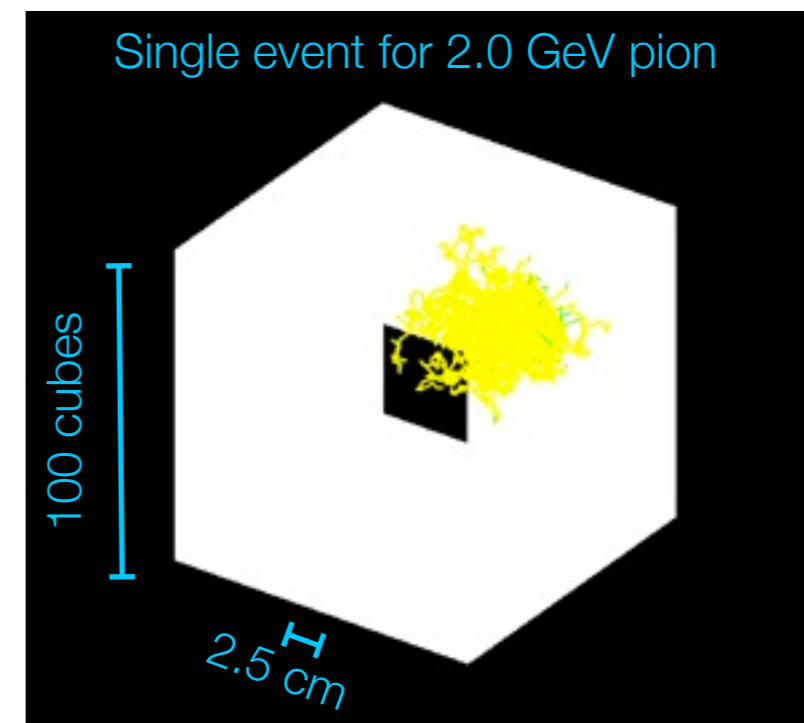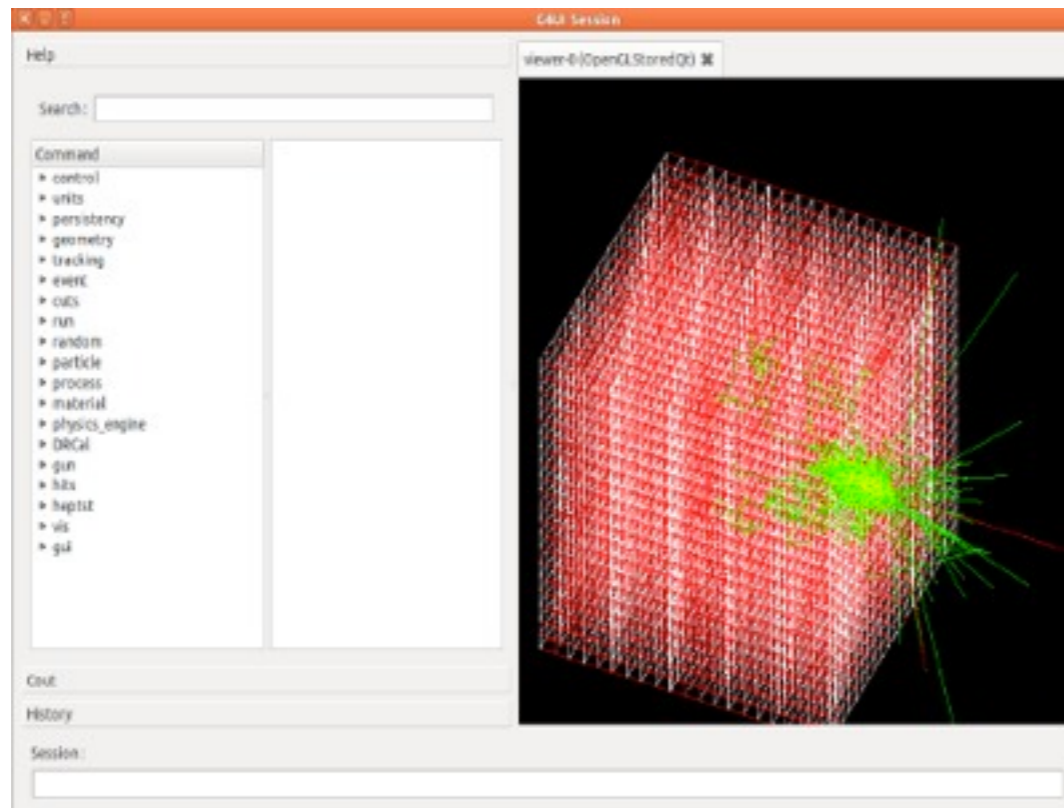
Makes working with Geant4 easy, without having to know the details about Geant4!

Energy response correction for a Dual Readout Calorimeter (Calibration.cc)

Analyze electron energy response to obtain calibration factor

Calibrate scintillation and Cherenkov response for electron

Calibrate scintillation and Cherenkov response for charged pions

Get Dual Readout correction factor

Correct for charged pion response

The slope of the curve is used as the calibration for scintillation response.

$$\text{calibration factor} = \frac{1}{m_{scint}}$$

BGO calorimeter, Physics list FTFPBERT

Electron scintillation response

We fit this curve to a third degree polynomial to obtain the dual correction factor

$$f_c = p_0 + p_1 x + p_2 x^2 + p_3 x^3$$

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Sampling Study

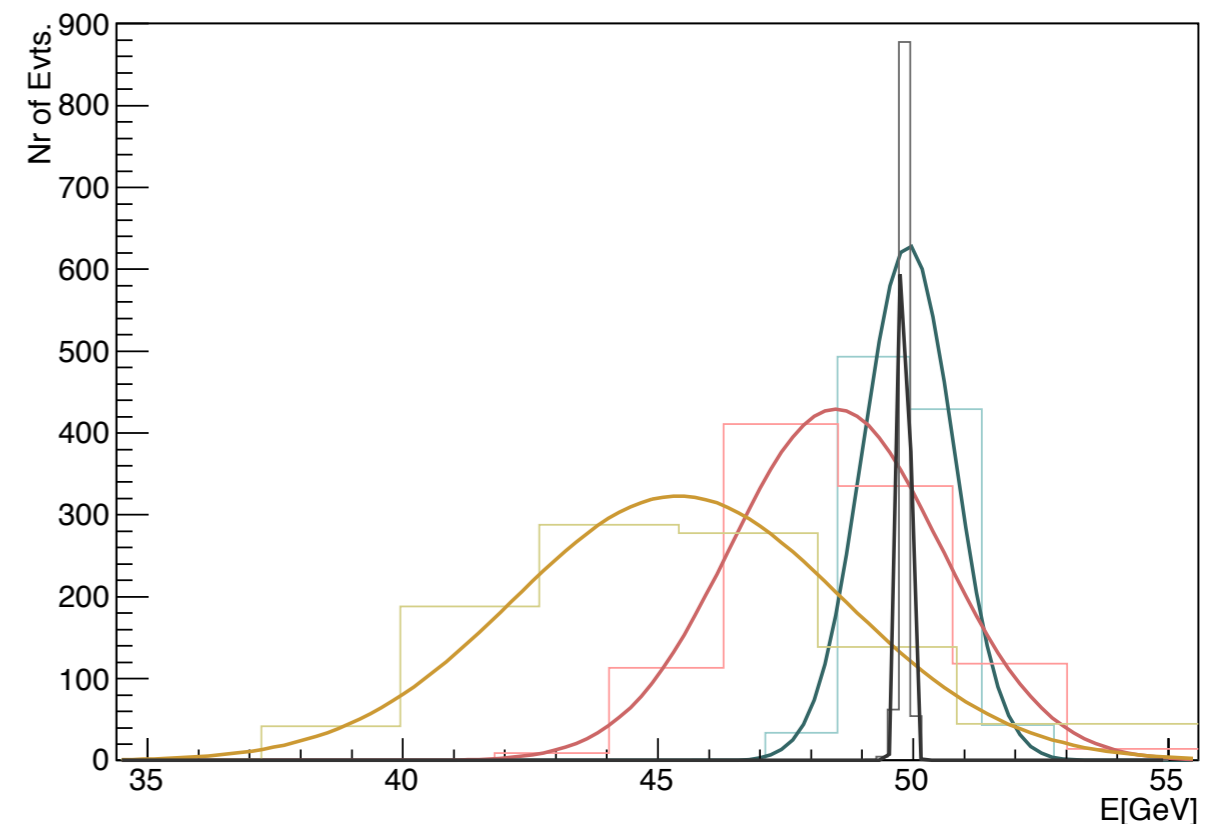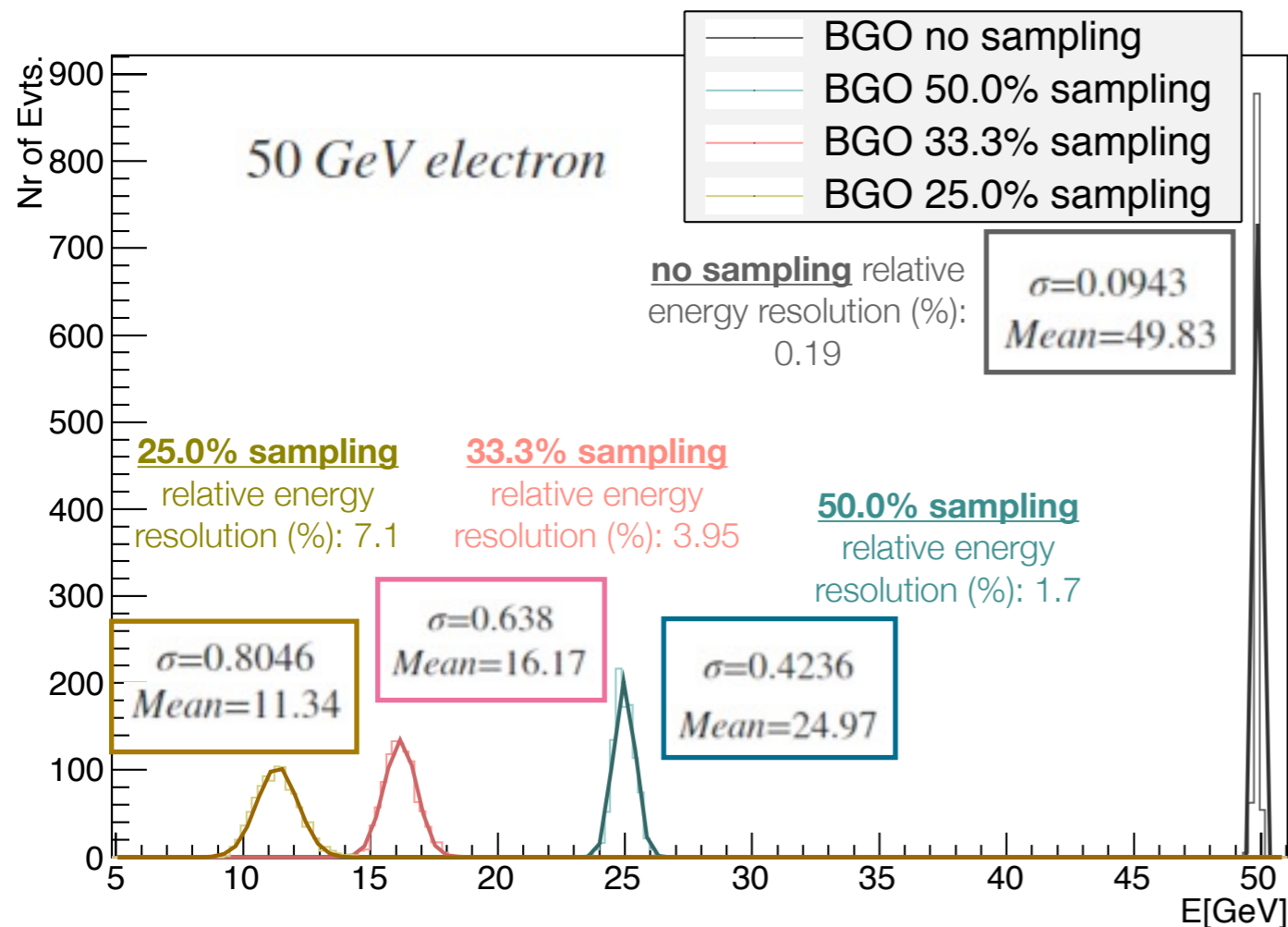*50.0% sampling:* we read every other layer.

33.3% sampling: we read one out of three layers.

25.0% sampling: we read one out of four layers.

In all cases we read the first layer!

Longitudinal segmentation with respect to incoming beam!

Each layer is 2.5 cm thick

100 layers in total

50 GeV electron

BGO no sampling
BGO 50.0% sampling
BGO 33.3% sampling
BGO 25.0% sampling

no sampling relative energy resolution (%): 0.19

$\sigma=0.0943$
$Mean=49.83$

25.0% sampling relative energy resolution (%): 7.1

33.3% sampling relative energy resolution (%): 3.95

50.0% sampling relative energy resolution (%): 1.7

$\sigma=0.8046$
$Mean=11.34$

$\sigma=0.638$
$Mean=16.17$

$\sigma=0.4236$
$Mean=24.97$

Sampling Study

Relative energy resolution (%) vs $1/\sqrt{E_{in}}$

Legend:
- BGO no sampling
- BGO 50.0% sampling
- BGO 33.3% sampling
- BGO 25.0% sampling

$$\sigma = c_1 + \frac{c_2}{\sqrt{E_{in}}}$$

	c1	c2
BGO no sampling	0.0294	10.4486
BGO 50.0% sampling	0.1577	25.6327
BGO 33.3% sampling	0.5561	35.4617
BGO 25.0% sampling	2.56	41.2215

50.0 GeV incident π^-

no sampling
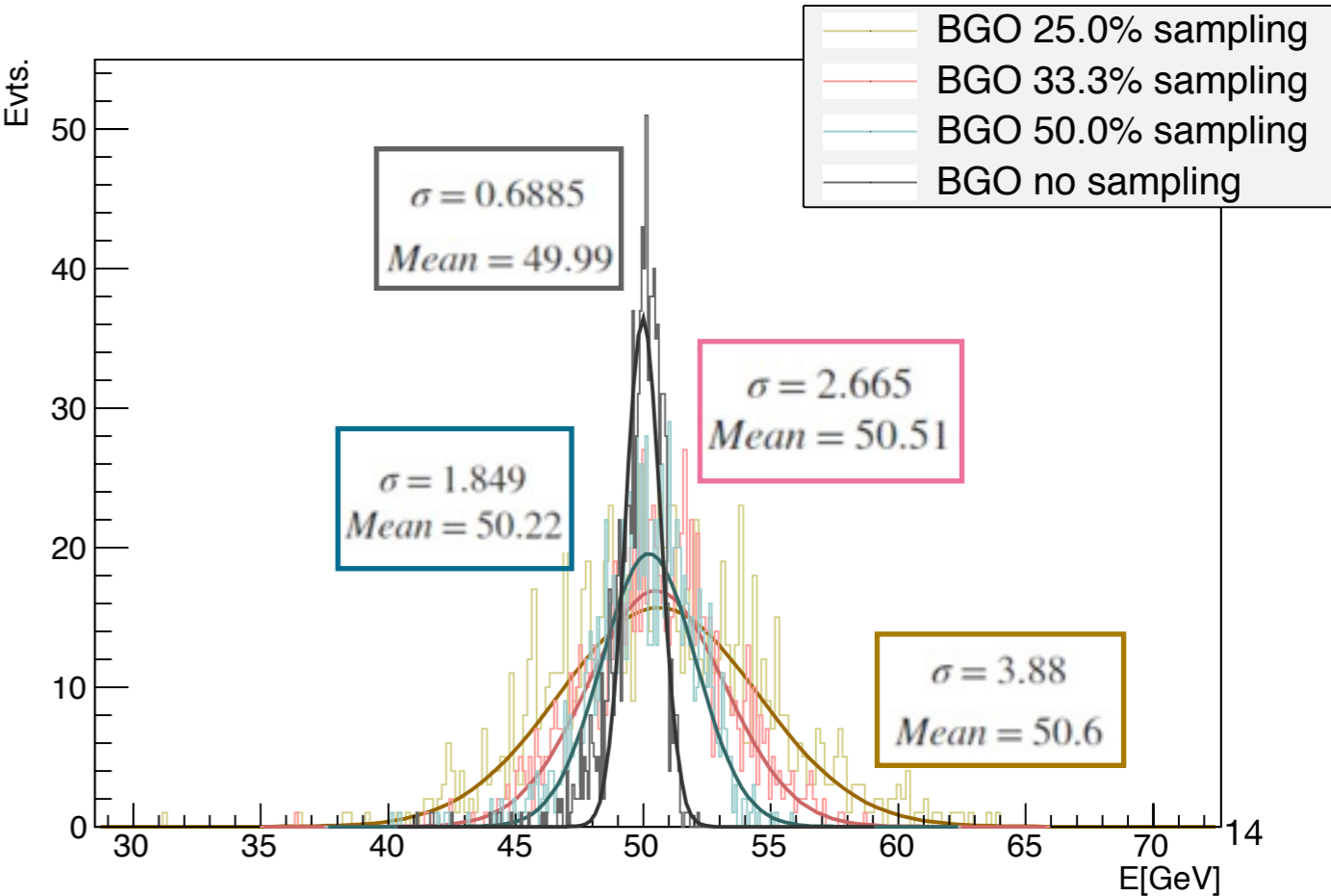relative energy resolution (%): 1.38

33.3% sampling
relative energy resolution (%): 5.28

50.0% sampling
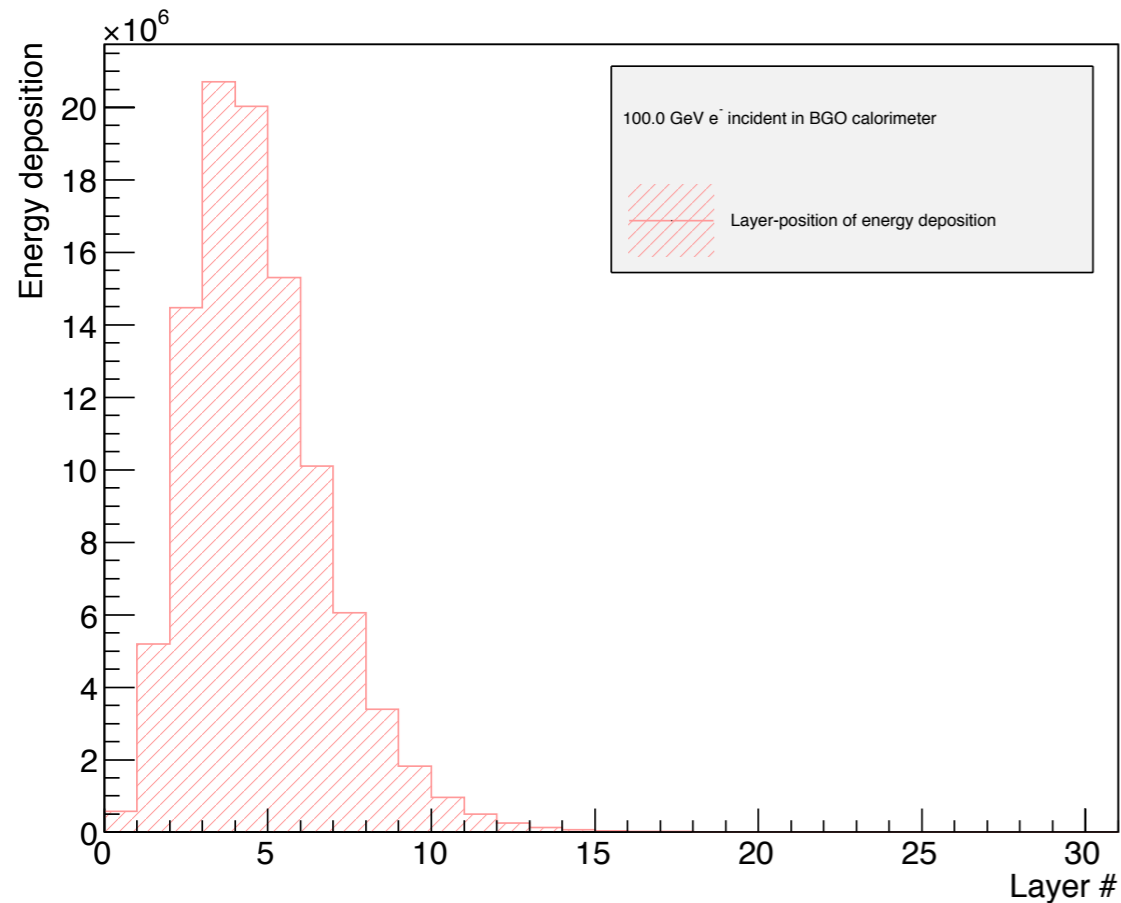relative energy resolution (%): 3.68

25.0% sampling
relative energy resolution (%): 7.67

Legend:
- BGO 25.0% sampling
- BGO 33.3% sampling
- BGO 50.0% sampling
- BGO no sampling

$\sigma = 0.6885$
$Mean = 49.99$

$\sigma = 2.665$
$Mean = 50.51$

$\sigma = 1.849$
$Mean = 50.22$

$\sigma = 3.88$
$Mean = 50.6$

E[GeV]

33.3% Sampling detailed study

100.0 GeV e⁻ incident in BGO calorimeter

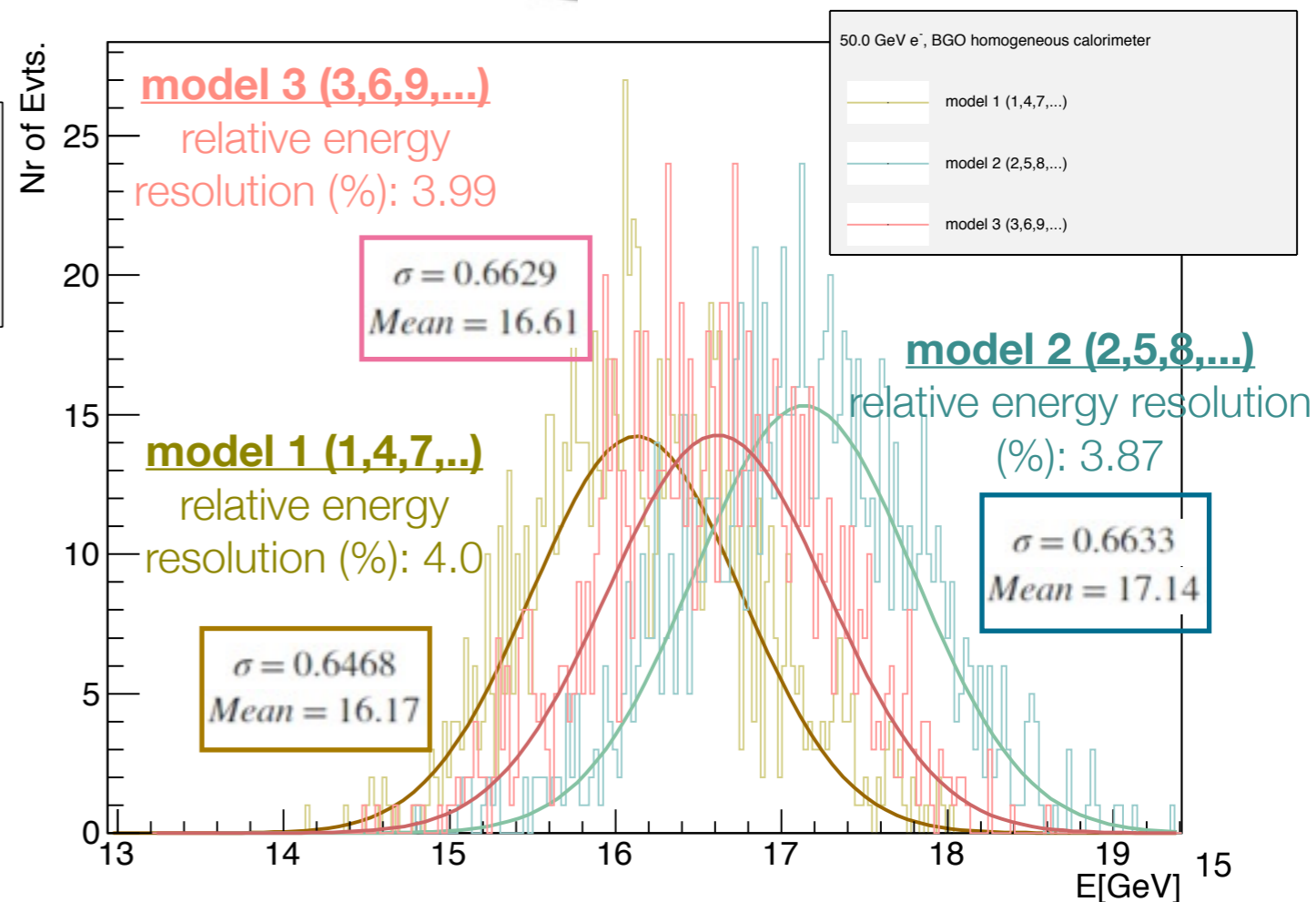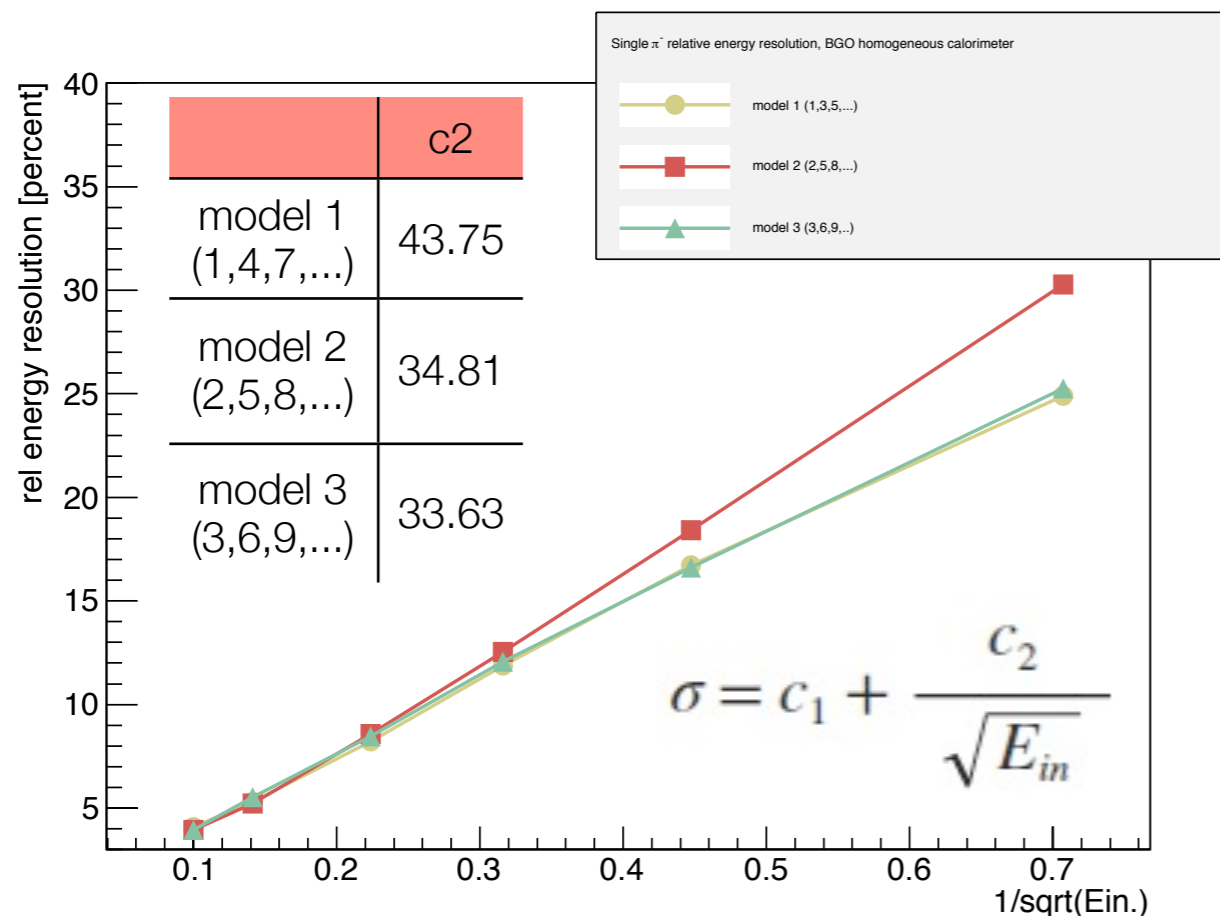Layer-position of energy deposition

Objective: To study the effect the longitudinal profile of the em shower has on sampling resolution.

Radiation length comparable to layer width

$$X_{0, BGO} : 11.2 \, mm$$

3 scenarios:
- model 1 (1,4,7,...)
- model 2 (2,5,8,...)
- model 3 (3,6,9,...)

	c2
model 1 (1,4,7,...)	43.75
model 2 (2,5,8,...)	34.81
model 3 (3,6,9,...)	33.63

Single π⁻ relative energy resolution, BGO homogeneous calorimeter

- model 1 (1,3,5,...)
- model 2 (2,5,8,...)
- model 3 (3,6,9,..)

$$\sigma = c_1 + \frac{c_2}{\sqrt{E_{in}}}$$

model 3 (3,6,9,...) relative energy resolution (%): 3.99

$\sigma = 0.6629$
$Mean = 16.61$

model 2 (2,5,8,...) relative energy resolution (%): 3.87

$\sigma = 0.6633$
$Mean = 17.14$

model 1 (1,4,7,..) relative energy resolution (%): 4.0

$\sigma = 0.6468$
$Mean = 16.17$

50.0 GeV e⁻, BGO homogeneous calorimeter

- model 1 (1,4,7,...)
- model 2 (2,5,8,...)
- model 3 (3,6,9,...)

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Summary

- We were able to manipulate tools provided by Geant4 to successfully simulate a Dual Readout Calorimeter as well as to make use of the analysis tools provided by ROOT. Both achieved by using C++ programing language.

- We have studied the details of shower development by looking at the average electromagnetic fraction, the longitudinal profile, and sampling fraction. In addition, we were able to study how different materials and incident particles may modify the behavior of the calorimeter response as well as to develop the necessary tools to establish a correlation between these factors.

- We were able to estimate the resolution one can achieve with such a device by manipulating the fluctuations involved in the process such as the sampling fraction, optical properties of the material, containment, etc.

- We were able to compare Geant4 results to empirical formulas found in literature (longitudinal shower profile, average electromagnetic fraction, etc.).

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Acknowledgements

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- Dr. Wenzel for his patience, guidance and support. For the invaluable knowledge I have gained from this experience.

- Dr. Para for his advice and guidance.

- My family, Elvis, Grecia, and Michelle for their support outside the cubicle.
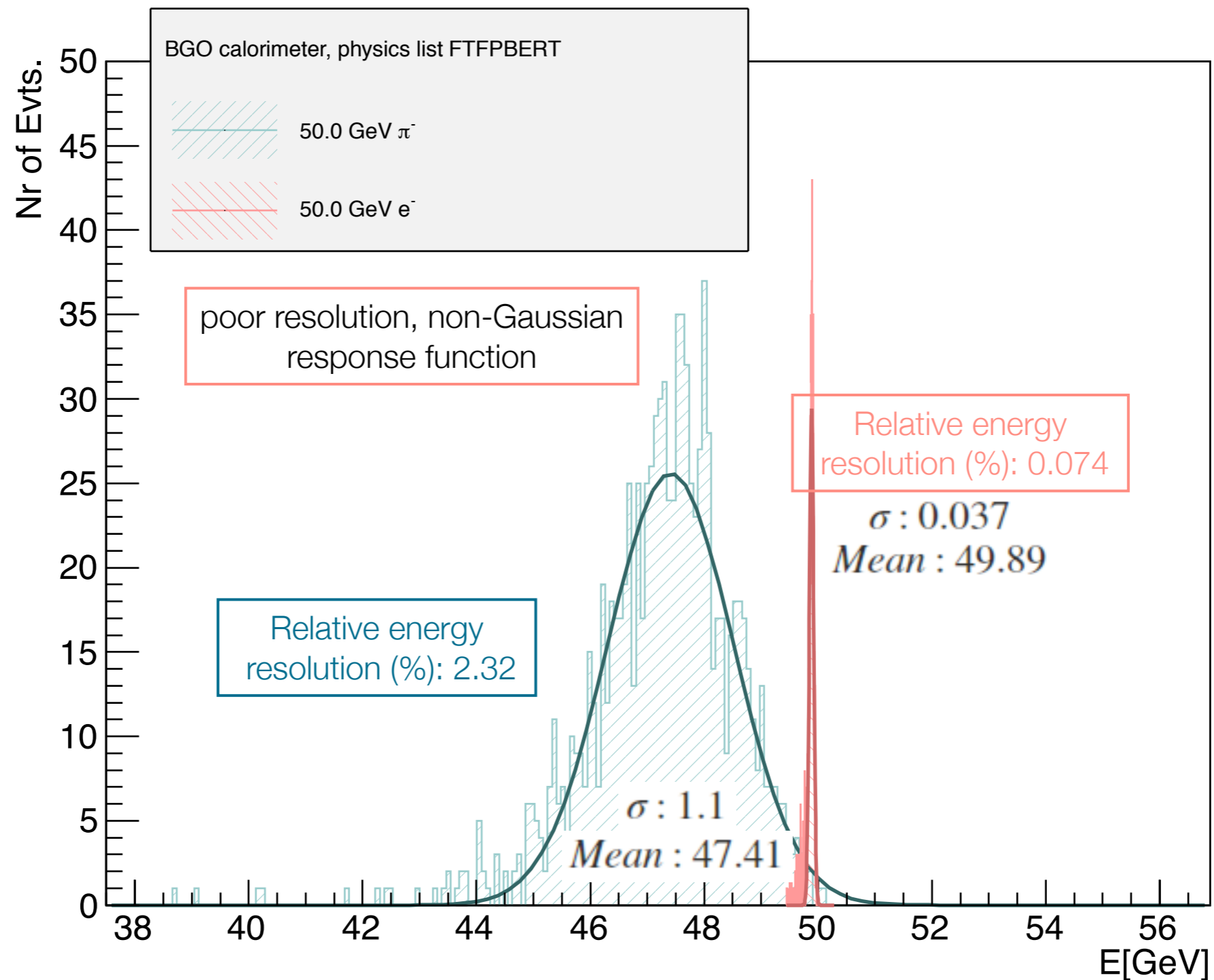
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Thank you!

Bibliography/References

- Fig.1.1. : http://hep.phys.sfu.ca/~kka34/kiosk/etours/etours_exper/experiment-09.html

- Fig. 1.2. : http://www.springerimages.com/img/Images/Springer/PUB=Springer_Netherlands-Dordrecht/JOU=10686/VOL=2009.25/ISU=1-3/ART=2009_9151/MediaObjects/MEDIUM_10686_2009_9151_Fig2_HTML.jpg

- Fig. 1.3. : http://scienceblogs.com/startswithabang/wp-content/blogs.dir/311/files/2012/04/i-e58d602f3875252700ae3a6852069086-cerenkov.jpg

Backslides

Backslides

Backslides

Radiation length	=	Related to the distance over which a high energy (> 1GeV) electron or position loses, on average, 63.2% of its energy to bremsstrahlung (~10 cm).
Nuclear interaction length	=	Related to the average distance a high energy hadron has to travel inside a medium before a nuclear interaction occurs.

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