Simulation Studies of a Homogeneous Total Absorption Dual Readout Calorimeter

Andrea Delgado,
Texas A&M University

Half a century of Calorimetry

Science ⟷ Technology

Particle physics has not been the exception!

Bubble chamber, scintillation counters, PMT's, gamma-ray counters...

- The ability to select the "interesting" events to study (*triggering*),
- Reduce the *amount of time* involved in analyzing pictures in bubble chambers,
- *Precision* of the information provided increases with increasing energy (*whereas in bubble chamber decreases since we measure the radius of curvature*),
- The emphasis of many experiments changed from a detailed *reconstruction of the four-vectors* of all the particles produced in the interaction process to a measure of *more global characteristics* (*i.e. energy flow*)

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

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

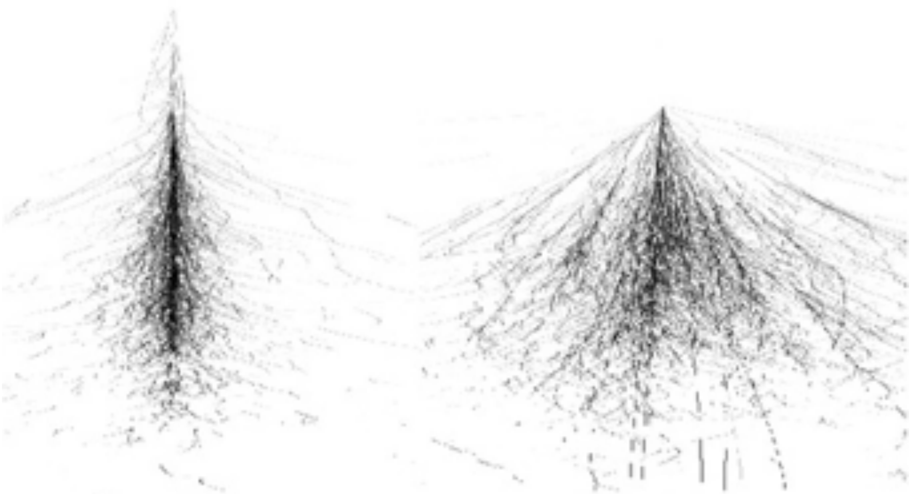
whereas

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

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

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*)



Gamma shower

Hadronic shower

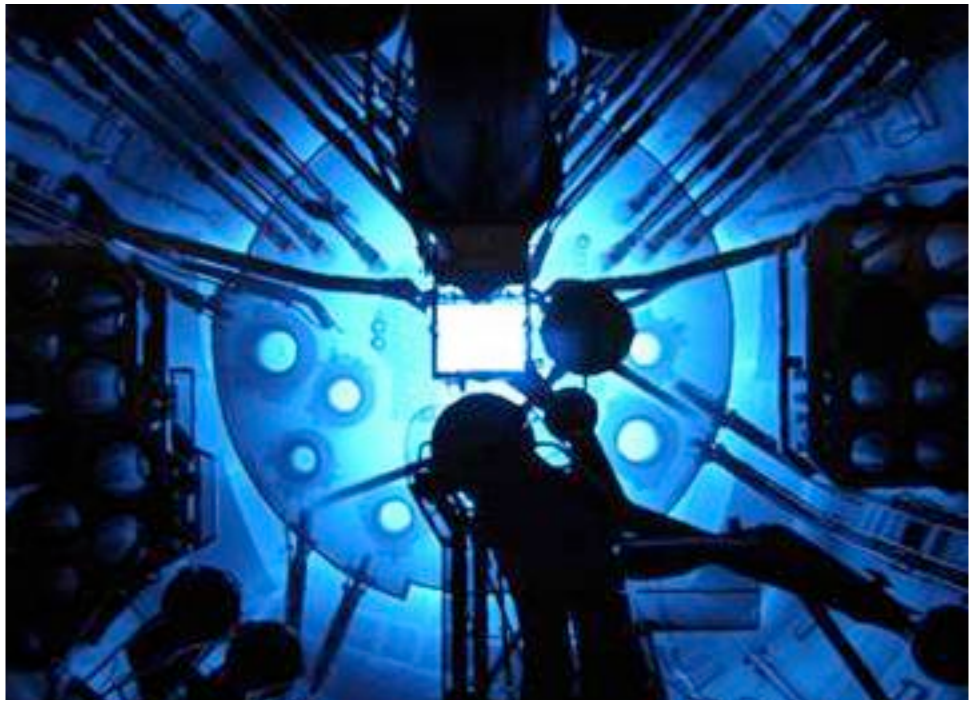
For e&m showers,

measured energy ~ energy of incoming particle

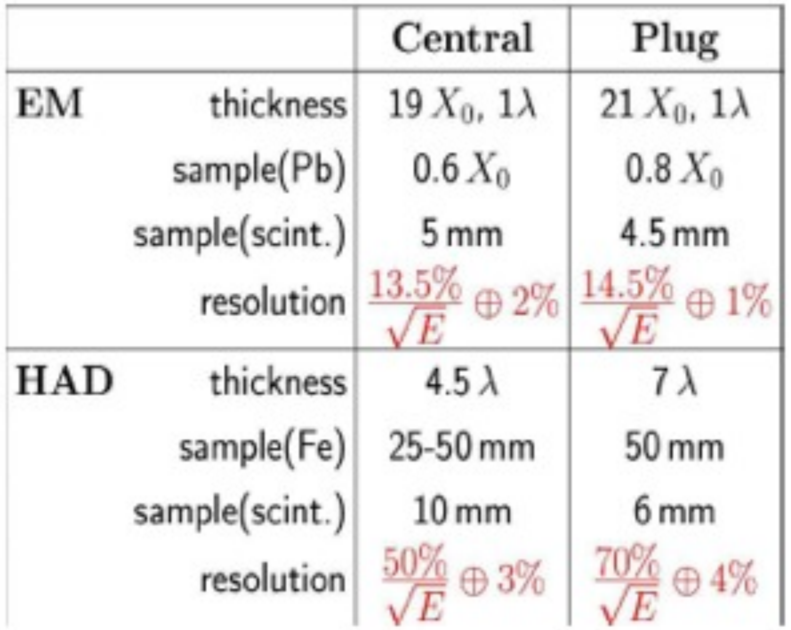
Detection Mechanisms

- **Scintillation light:** produced when unstable atoms in excited state return to ground state.
- **Čerenkov light:** produced when a charged particle travels faster than the speed of light in a certain medium.

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



The Collider Detector at Fermilab



		Central	Plug
EM	thickness	$19\,X_0$, 1λ	$21\,X_0$, 1λ
	sample(Pb)	$0.6\,X_0$	$0.8\,X_0$
	sample(scint.)	5 mm	4.5 mm
	resolution	$\frac{13.5\%}{\sqrt{E}} \oplus 2\%$	$\frac{14.5\%}{\sqrt{E}} \oplus 1\%$
HAD	thickness	$4.5\,\lambda$	$7\,\lambda$
	sample(Fe)	25-50 mm	50 mm
	sample(scint.)	10 mm	6 mm
	resolution	$\frac{50\%}{\sqrt{E}} \oplus 3\%$	$\frac{70\%}{\sqrt{E}} \oplus 4\%$

$$\boxed{\frac{\sigma_E}{E} \sim \frac{1}{\sqrt{E}}}$$

Calorimeter types

Some calorimeters are built in two sections:

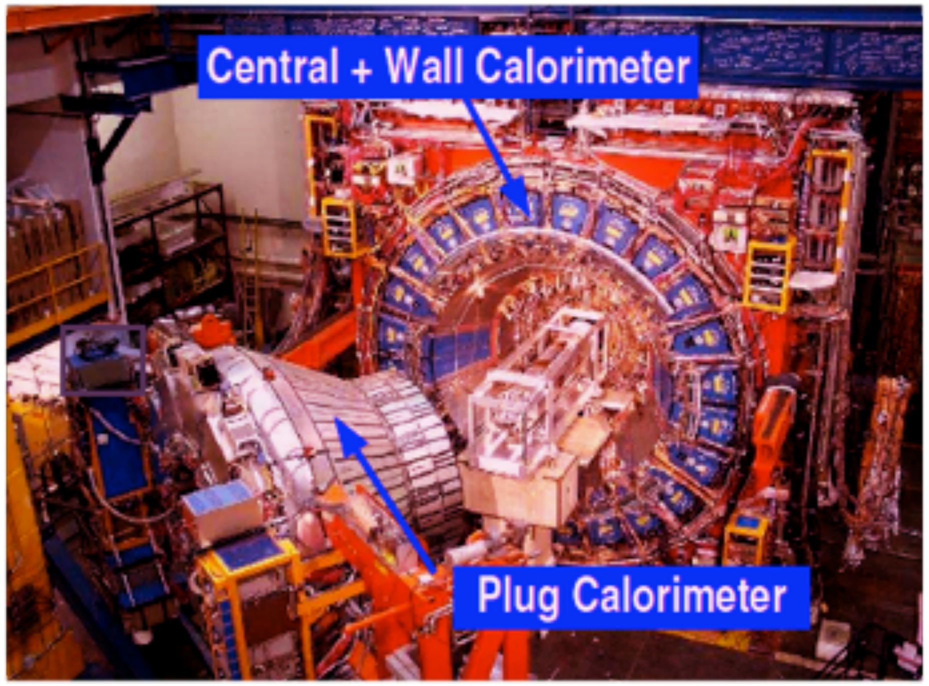
- **Electromagnetic**: Finer segmentation, smaller volume, enough to contain an e&m shower, electronics are usually more precise.
- **Hadronic**: Coarser segmentation, larger volume to contain a hadronic shower, usually worse resolution than the e&m section.

Radiation length (X_0) = 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 (λ) = Average distance a high energy hadron has to travel inside a medium before a nuclear interaction occurs.

Calorimeters can also be:

- **Homogeneous**: Entire volume is sensitive to the particles and may contribute to the signals generated by the detector (*i.e. the functions of absorbing the particles and detecting the signals produced in this process are exercised by the same material*).
- **Sampling**: Particle absorption and signal generation are exercised by different materials:
  - *Active medium*: Generates the light or charge that forms the basis for the signals [*crystal, plastic,..*]
  - *Passive medium*: Usually a high density material that absorbs the particle [*copper, lead, iron, uranium,..*]



Average value of Electromagnetic Fraction

Some particles produced in the *hadronic cascade* decay through electromagnetic interaction of the form:

$$\pi^0, \eta \rightarrow \gamma\gamma$$

Hadron showers generally contain a component that propagates electromagnetically [average electromagnetic fraction $\langle f_{em} \rangle$]. This component is defined in several ways:

- Some people defines it as the energy deposited in the calorimeter by means of the kinetic energy of π^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 (*i.e. energy available for these processes to occur leads to different interactions*)
- 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.

Average value of Electromagnetic Fraction

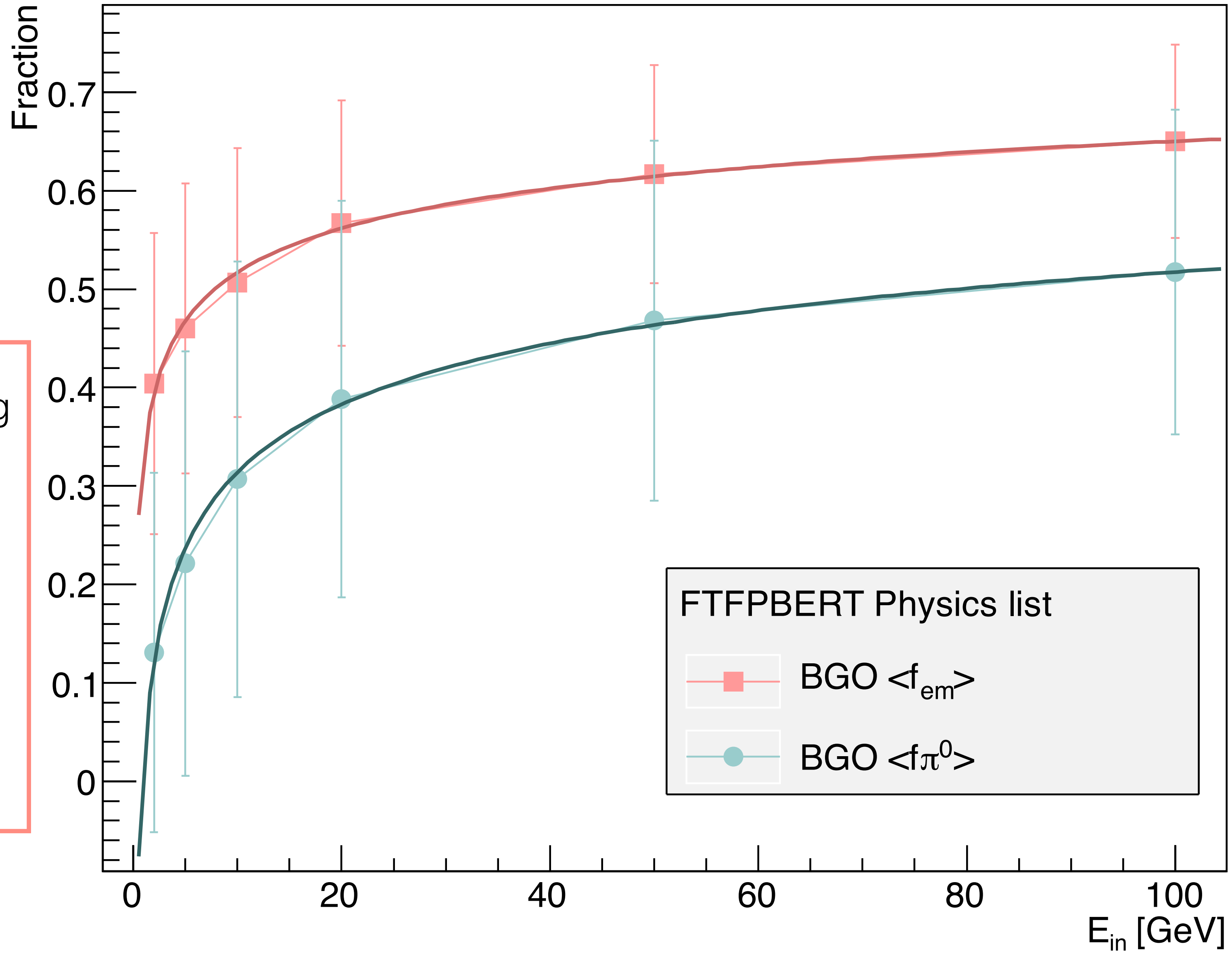
The average value of the electromagnetic fraction usually obeys the empirical power law:

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

where:

E_0 : a scaling factor corresponding to the average energy needed for production of one pion (~ 1GeV for incident charged pions)

$m-1$: is related to the average multiplicity and the average fraction of neutral pions produced (~ 0.80-0.87)



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* scintillating crystals/glasses (currently a R&D program to find affordable crystals).
- The availability of robust, compact, and inexpensive silicon PMT’s.

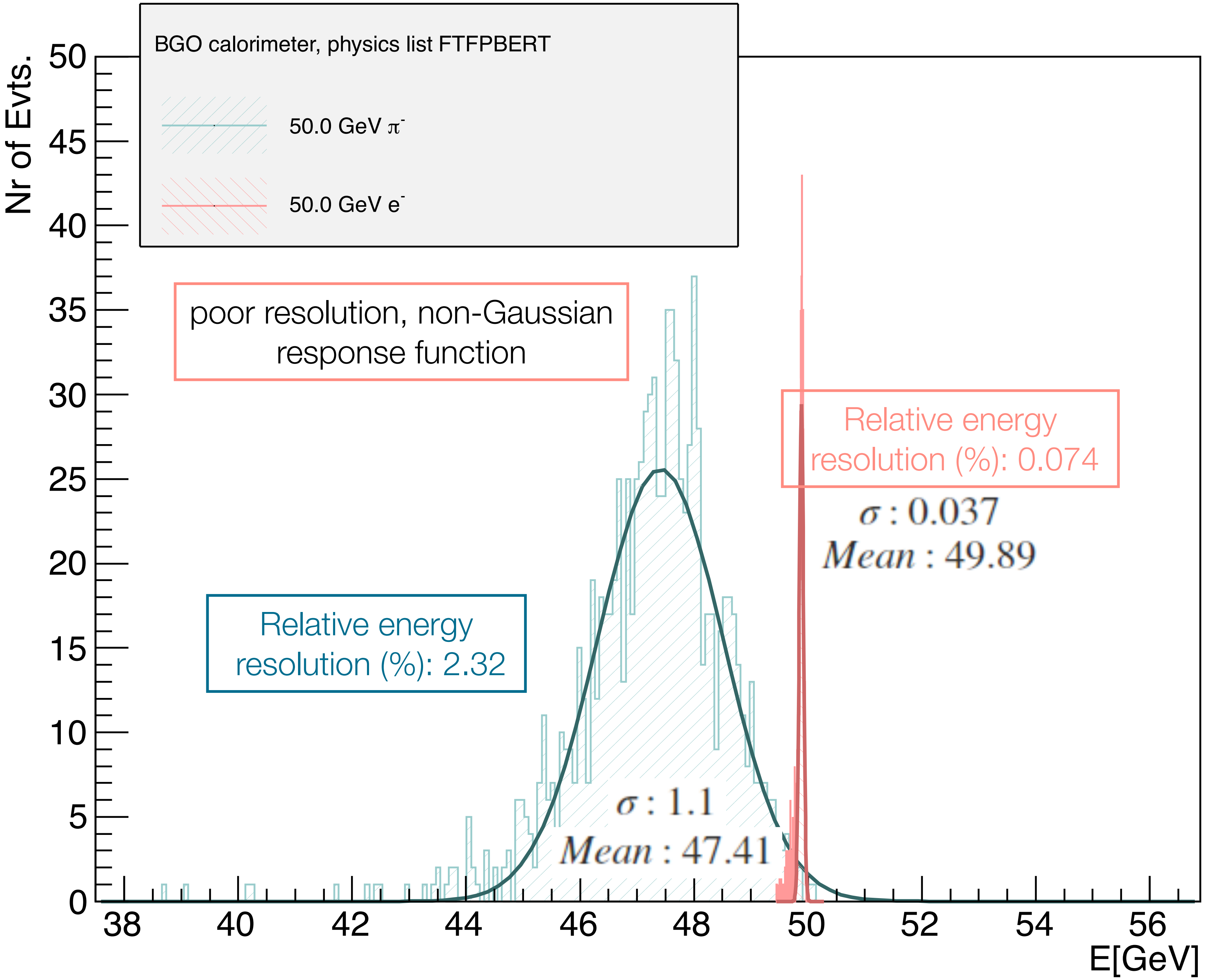
Motivation for a HomogeneousTotal Absorption Dual Readout Calorimeter

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

- **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.* Homogeneous
- **Difference in sampling fractions:** *fluctuations introduced from the difference in sampling fractions between the different materials.* Totally active
- **Leakage:** *Energy lost in 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!

Motivation for a Homogeneous Total Absorption Dual Readout Calorimeter (continued)

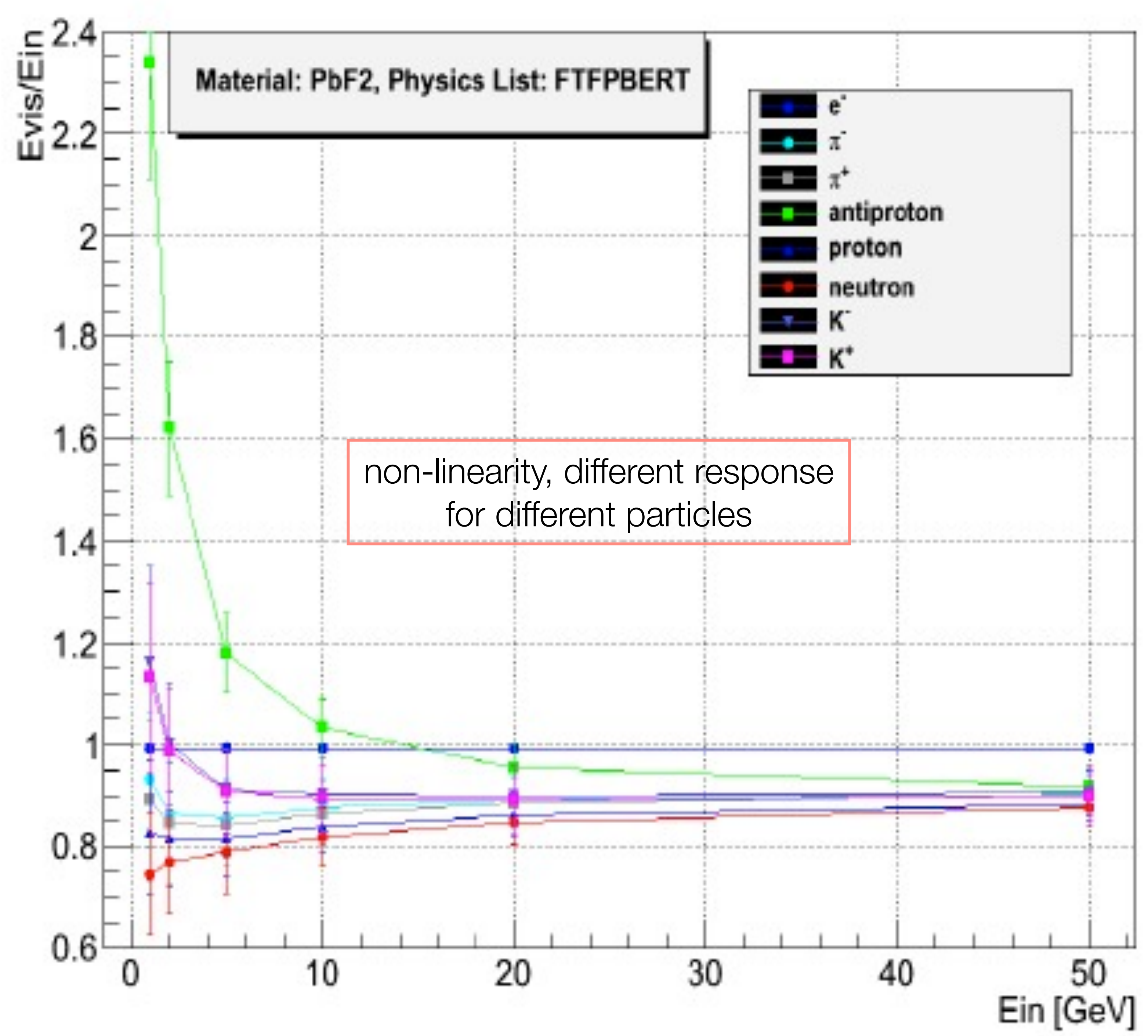


poor resolution, non-Gaussian response function

Relative energy resolution (%): 2.32

Relative energy resolution (%): 0.074

Motivation for a Homogeneous Total Absorption Dual Readout Calorimeter (continued)



non-linearity, different response for different particles

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 both scintillation and Cherenkov signals can be described as:

$$\boxed{\begin{aligned} \frac{S}{E} &= f_{em} \cdot e + (1 - f_{em}) h_s \\ \frac{C}{E} &= f_{em} \cdot e + (1 - f_{em}) h_C \end{aligned}}$$

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:

$$E = S\left[\frac{(1 - h_C) - {}^{C}\!/_{S}(1 - h_S)}{h_s - h_c}\right]$$

Simulation Framework : CaTS (Calorimeter and Tracker Simulation

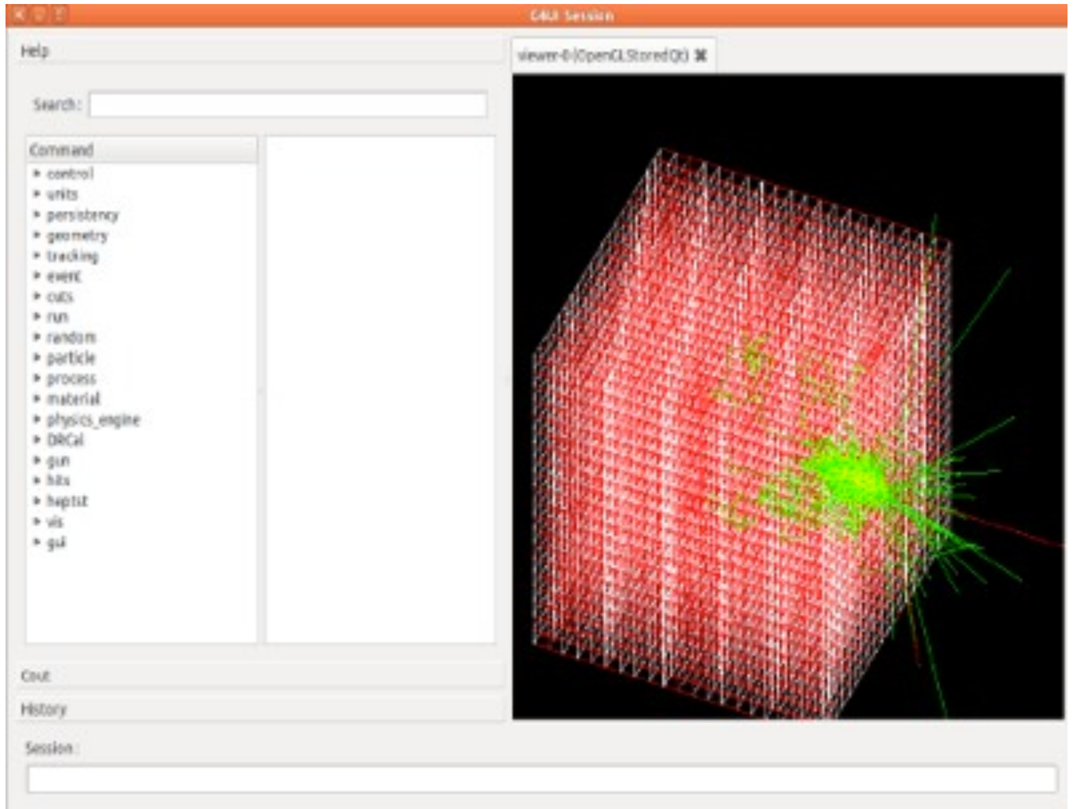
Created by Hans Wenzel, Paul Russo, Peter Hansen

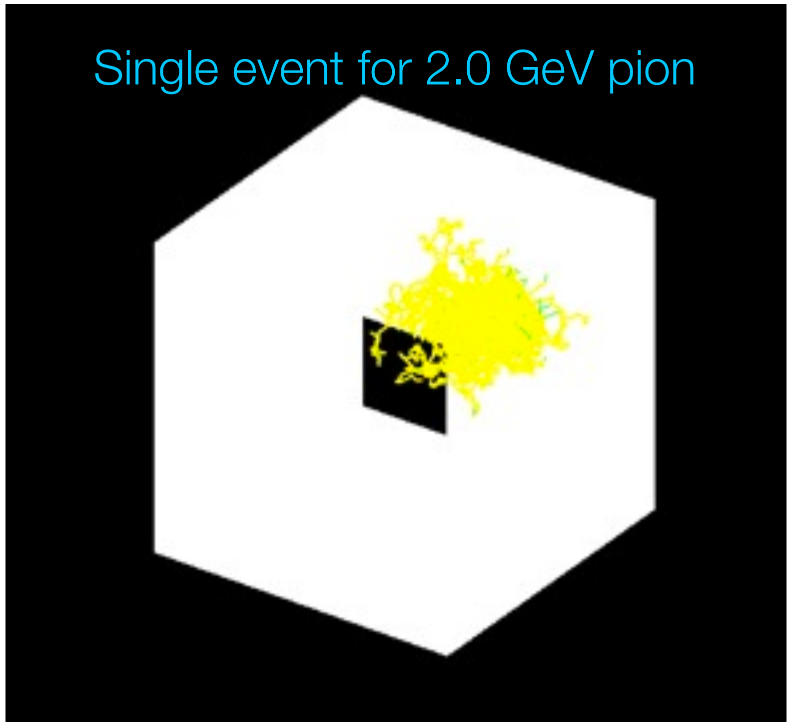
- A flexible and extendable framework based on Geant4 and ROOT for the general simulation of calorimeter and tracking detectors.

- Provides special sensitive detectors and Hit Classes that register both the energy deposited and the number of Cherenkov photons produced by particles above the Cherenkov threshold. This in order to be able to simulate Dual Readout calorimeters.

- Allows for the detailed study of single calorimeter cells by enabling the tracking of optical photons.

- Facilitates the description of the detector geometry by using a gdml file containing relevant optical properties [*refraction index, absorption length, scintillation yield, etc...*]




Single event for 2.0 GeV pion